Fault weakness during seismic slip

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Euro-conference of Rock Physics and Geomechanics on Natural hazards: thermo-hydro-mechanical processes in rocks

29th Course of the INTERNATIONAL SCHOOL OF GEOPHYSICS

Erice, 26 September 2007, Italy

S'Venerina Earthquake (Sicily, 2002)

Outline

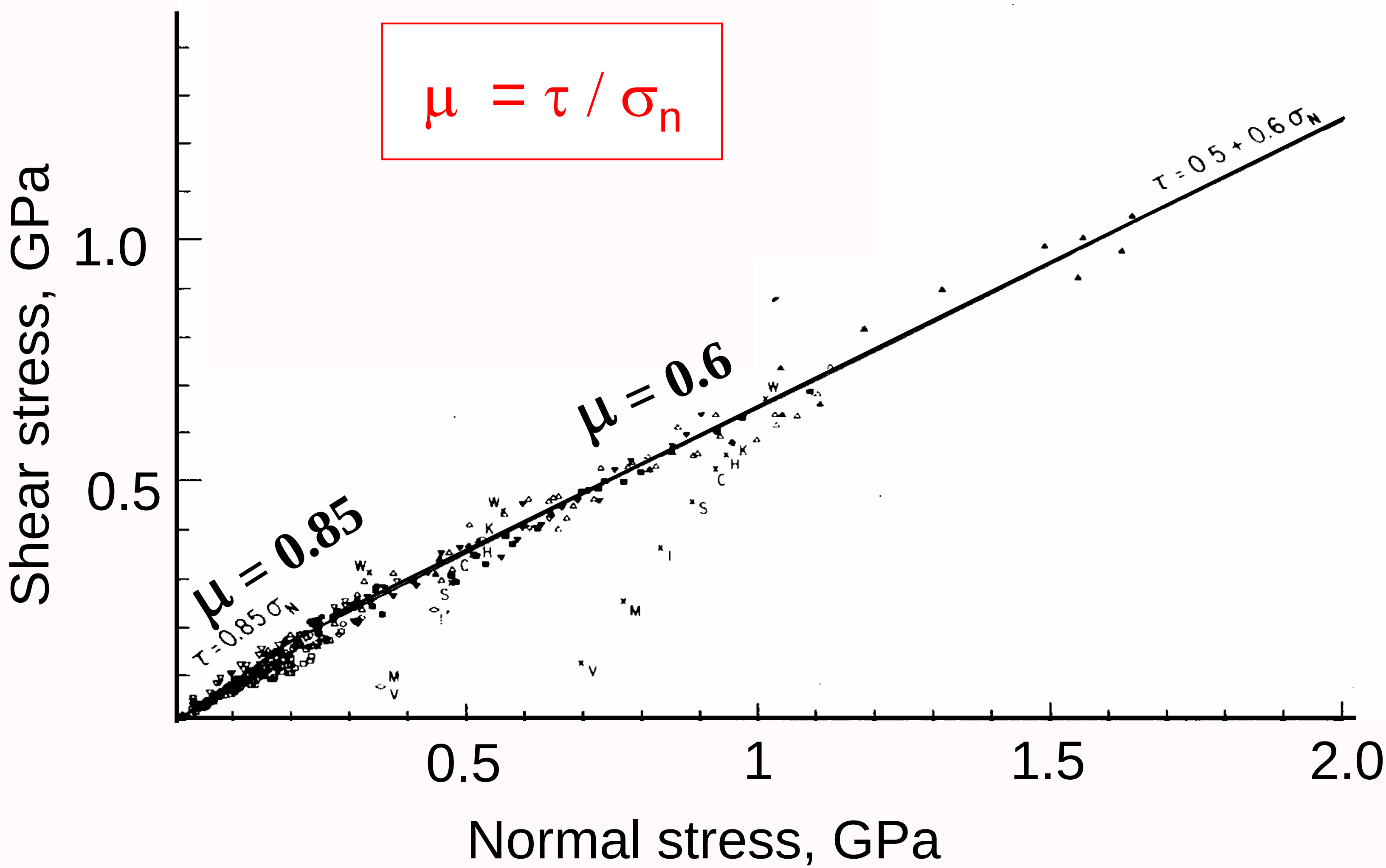
1. Rock friction

2. HV rock friction experiments (HVRFE)

    2a. Silica gel lubrication
    2b. Flash heating and dehydration weakening
    2c. Thermal decomposition weakening
    2d. Gouge-related weakening

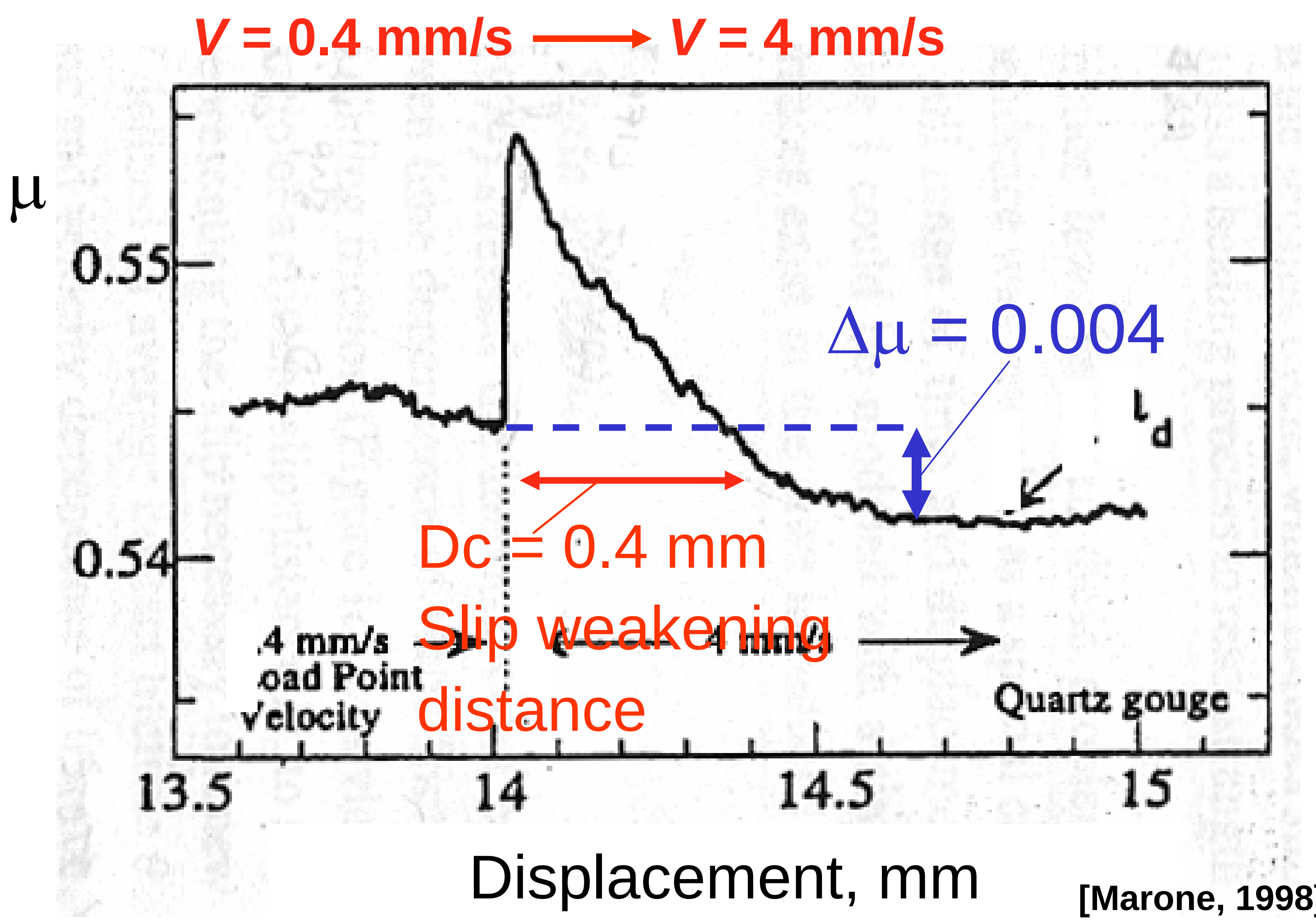
3. Extrapolation of experimental data to seismic slip:
   the case for melt lubrication

At slow slip rates (< 1 mm/s) and for short displacements (< 1 cm) rock friction (μ) is 0.6-0.8



[Byerlee, PAGEOPH,1978]

For small changes in V, μ varies of few % and the slip weakening distance is few hundreds microns



[Marone, 1998]

These experimental results found broad application in EQ mechanics.

But during earthquakes

- Slip rates of **0.1- 4 m/s (or ~ 1 m/s)**
- Displacements **up to 20 m**
- Dc (estimated to be) of **0.5 - 4 m**

Reduction in strength during EQ might determine:

1. Whether dynamic stress drop is larger than static stress drop.

2. Rupture propagation mode: self-healing pulse vs. crack-like.

3. Increase in the ratio of radiated energy vs. seismic moment with EQ size.

4. Low heat production during coseismic slip.

Fault weak. mech. proposed till 2001 μ

1. **Thermal pressurization of pore fluids** **0.0?**

   [*Sibson*, 1973]

2. **Normal interface vibrations** **0.0?**

   [*Brune et al*., 1993]

3. **Acoustic fluidization** **0.0?**

   [*Melosh*, 1996]

4. **Frictional melting (?)** **0.6-0.5**

   [*Spray*, 1993; *Tsutsumi and Shimamoto*, 1997]

5. **Flash heating** **0.0?**

   [*Rice,* 1999]

6. **Elastohydrodynamic lubrication** **0.0?**

   [*Brodsky and Kanamori*, 2001]

experimental data for rocks in yellow

Fault weak. mech. proposed 2002-2007 μ

1. **Gouge-related weakening** **< 0.2**

   [*Chambon et al.*, 2002; *Mizoguchi et al.*, 2007]

2. **Silica gel lubrication** **0.2**

   [*Goldsby and Tullis*, 2002]

3. **Melt lubrication** **0.1**

   [field & exper. evidence, *Di Toro et al.*, 2006]

4. **Flash heating and dehydration weakening** **0.1**

   [*Hirose and Bystricky*, 2007]

5. **Thermal decomposition weakening** **0.1**

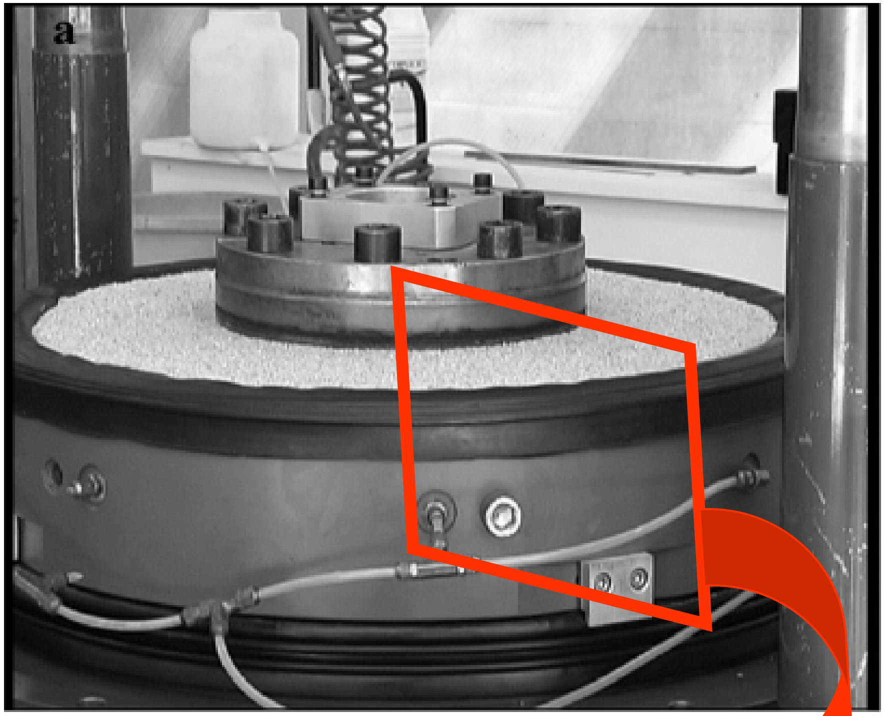
   [*Han et al.*, 2007]

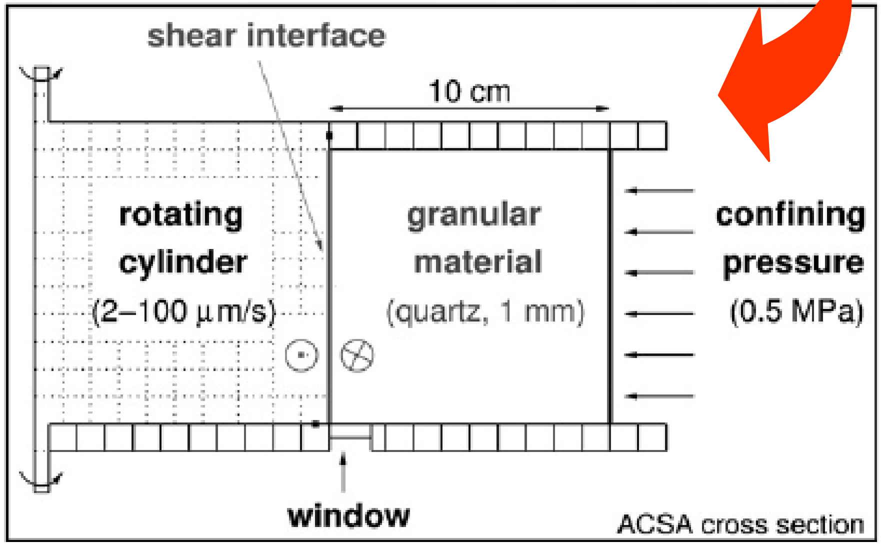
experimental data for rocks in yellow

Why all these new mechanisms?

New PhDs, new experiments and new machines…

Annular Simple Shear Apparatus



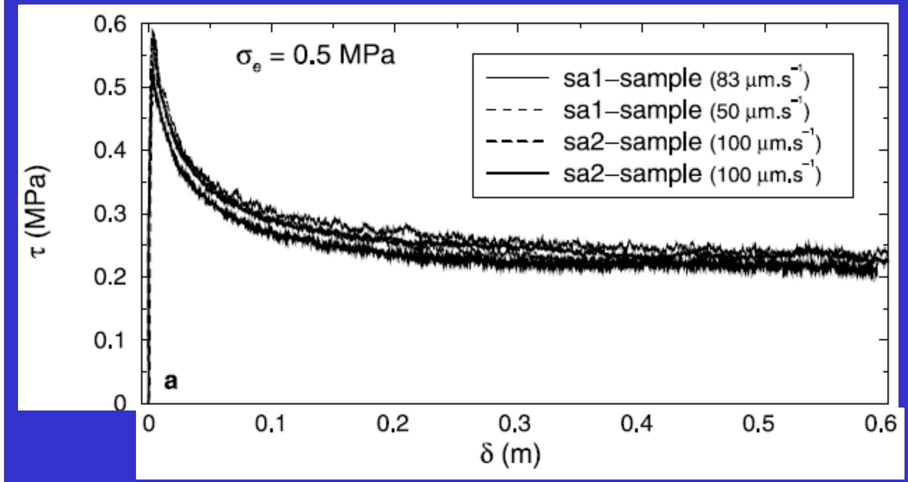


σ_n < 1 MPa

v = 0.001 – 0.1 mm/s

d < 50 m

Non-cohesive rocks



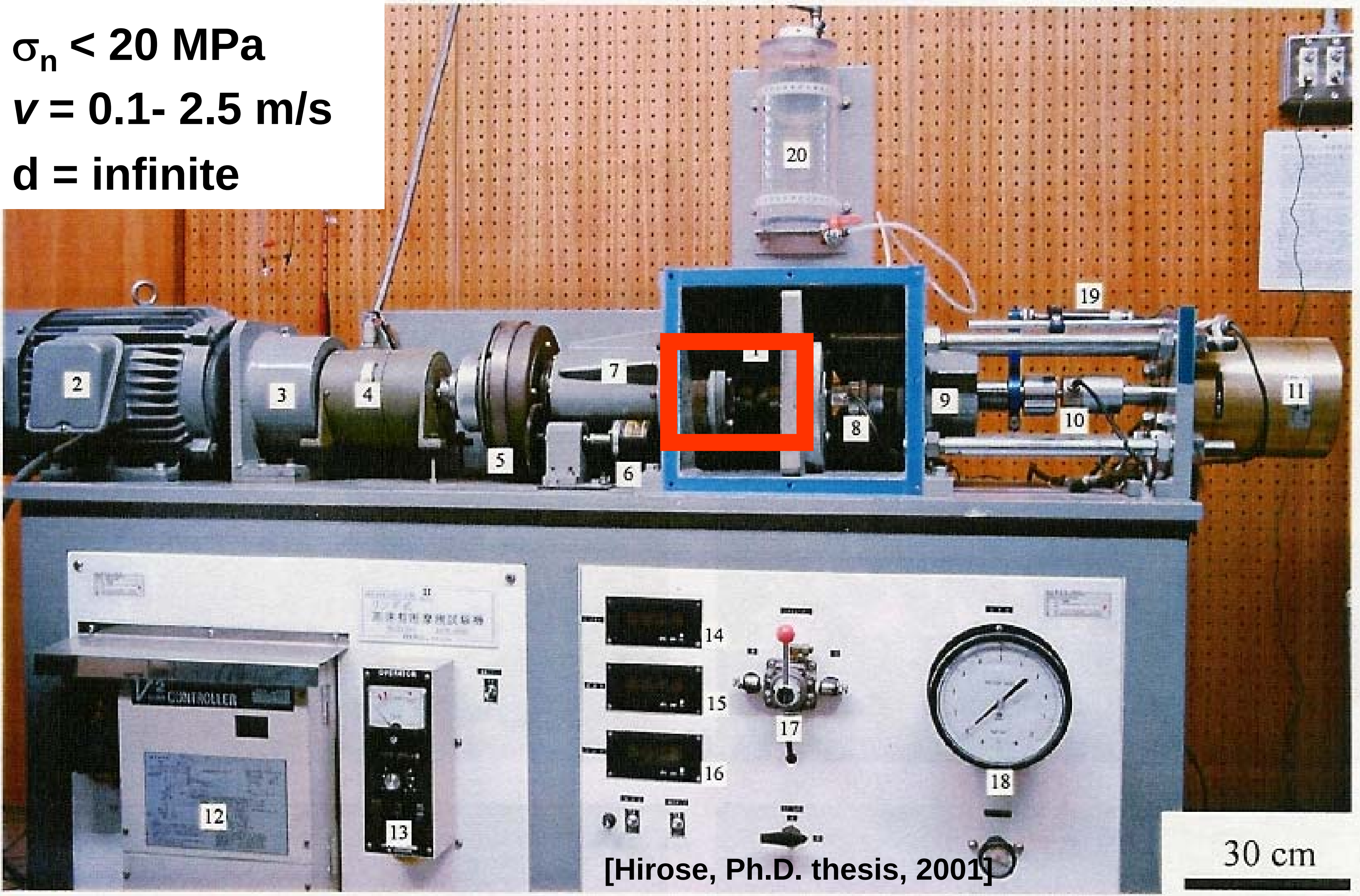
[Chambon et al. JGR, 2006]

HV rotary shear (1990, Kyoto) designed by Shimamoto

σ_n < 20 MPa

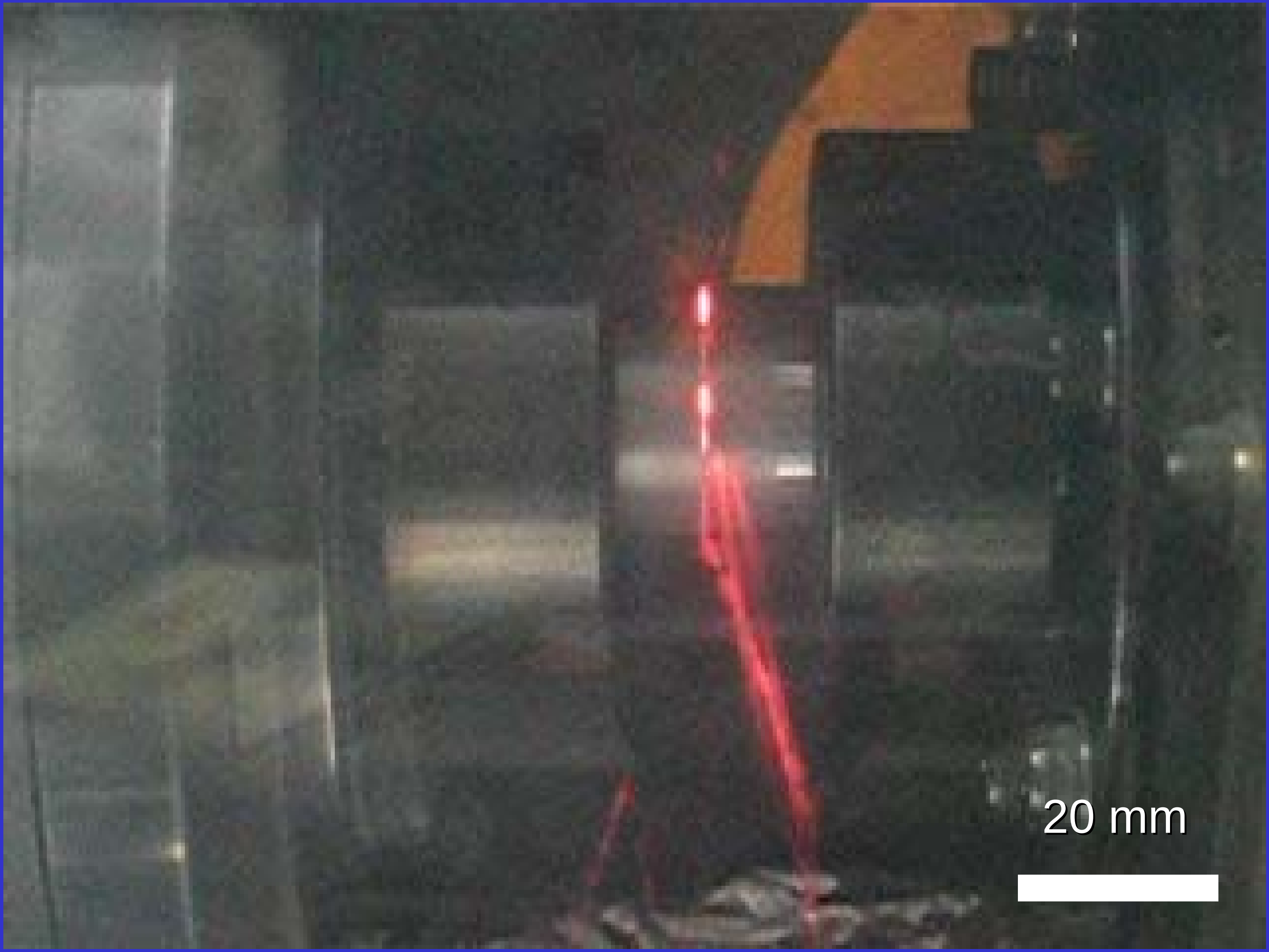
v = 0.1- 2.5 m/s

d = infinite



[Hirose, Ph.D. thesis, 2001]

Tonalite, v = 1.3 m/s, σ_n = 20 MPa



Higher performing machines are under development nowadays…

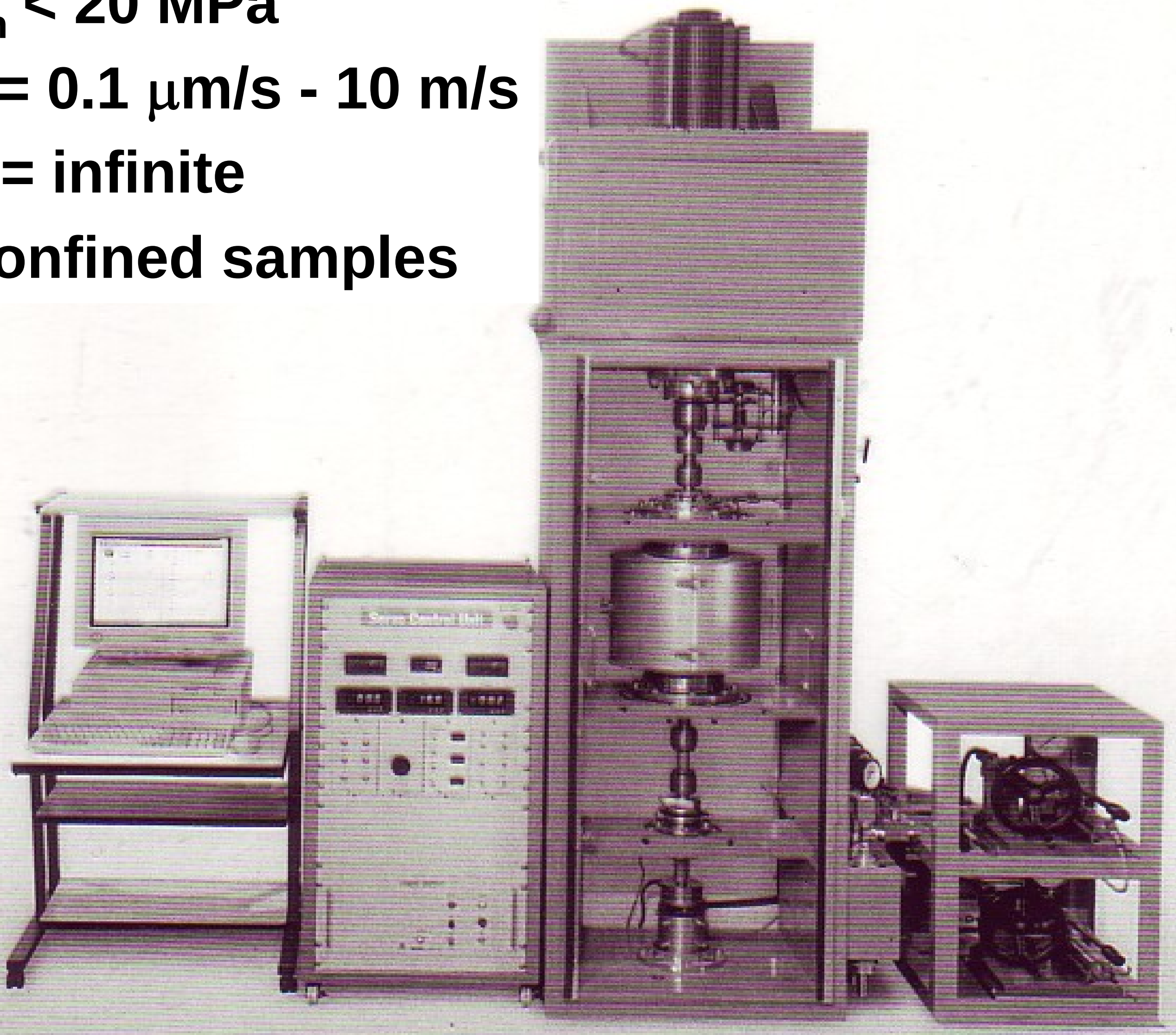
HV-Rock Friction Apparatus (2000-07)
designed by Shimamoto (Hiroshima, JPN)

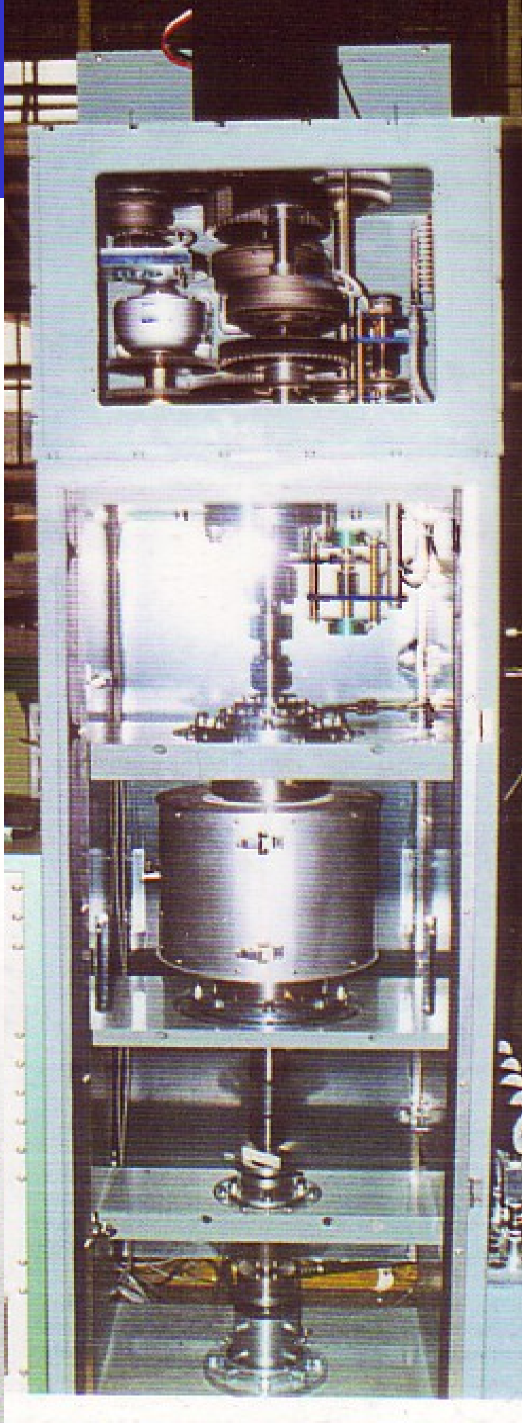
σ_n < 20 MPa

v = 0.1 μm/s - 10 m/s

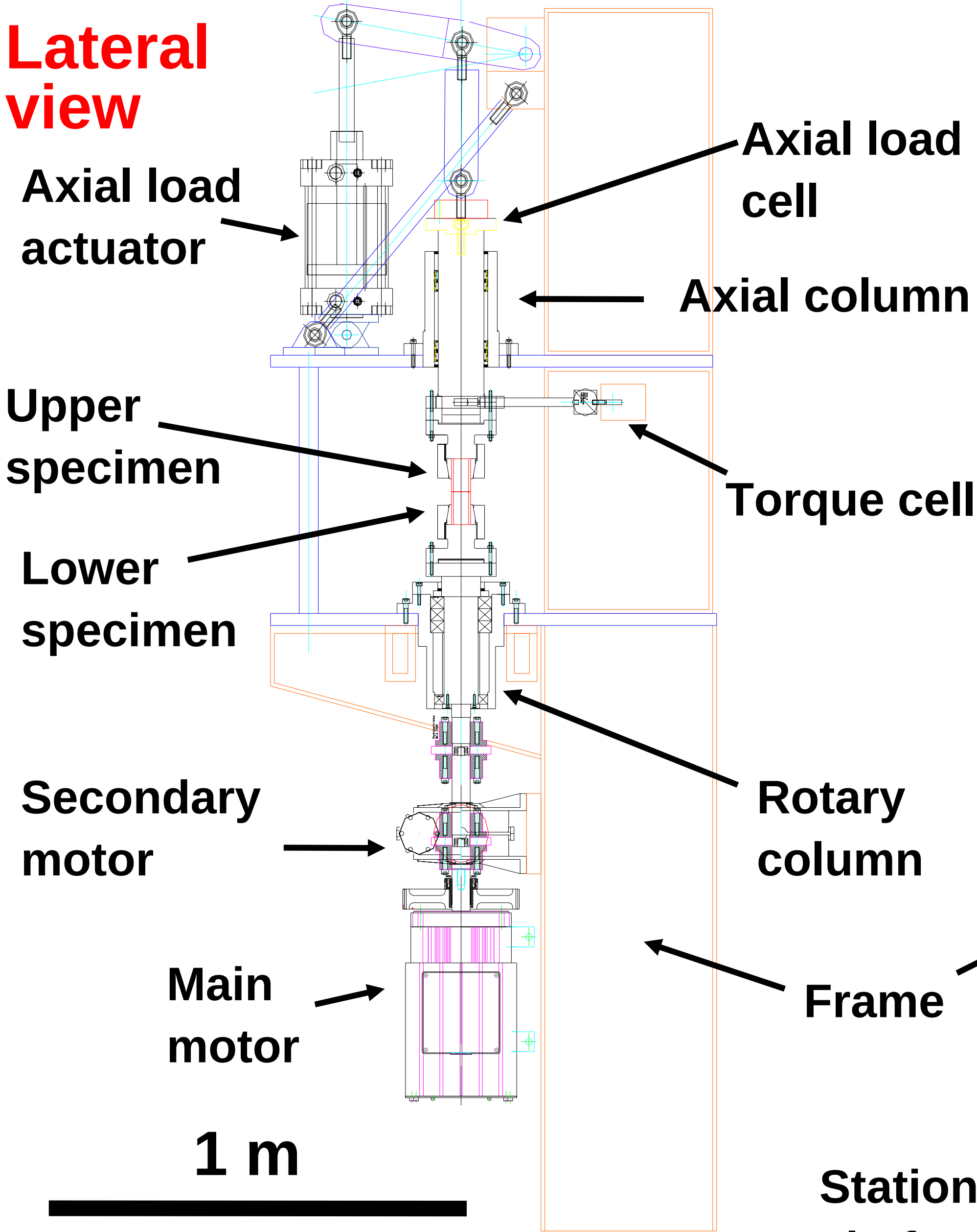
d = infinite

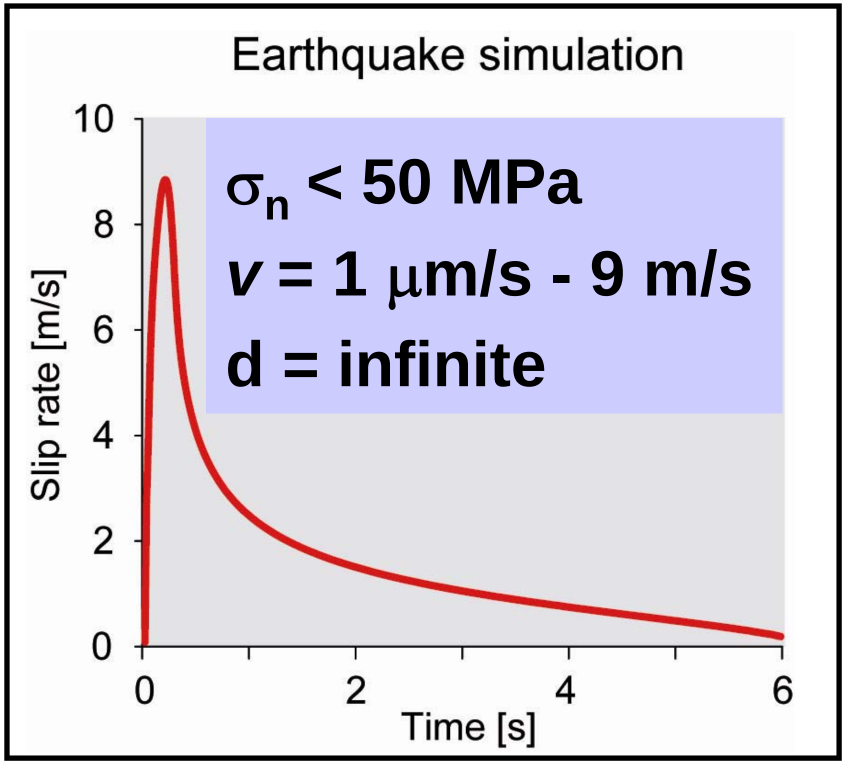
Confined samples

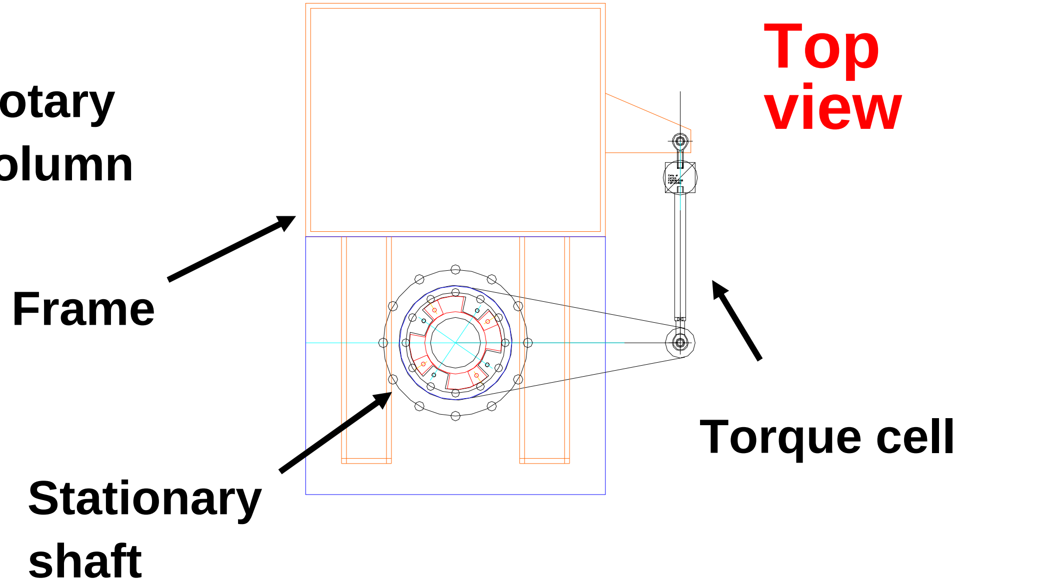




INGV in Rome?


Lateral view
Axial load actuator
Axial load cell
Axial column
Upper specimen
Torque cell
Lower specimen
Rotary column
Secondary motor
Frame
Main motor
1 m


Earthquake simulation
σ_n < 50 MPa
v = 1 μm/s - 9 m/s
d = infinite
Slip rate [m/s]
Time [s]
0
2
4
6
8
10


Top view
Torque cell
Stationary shaft

Outline

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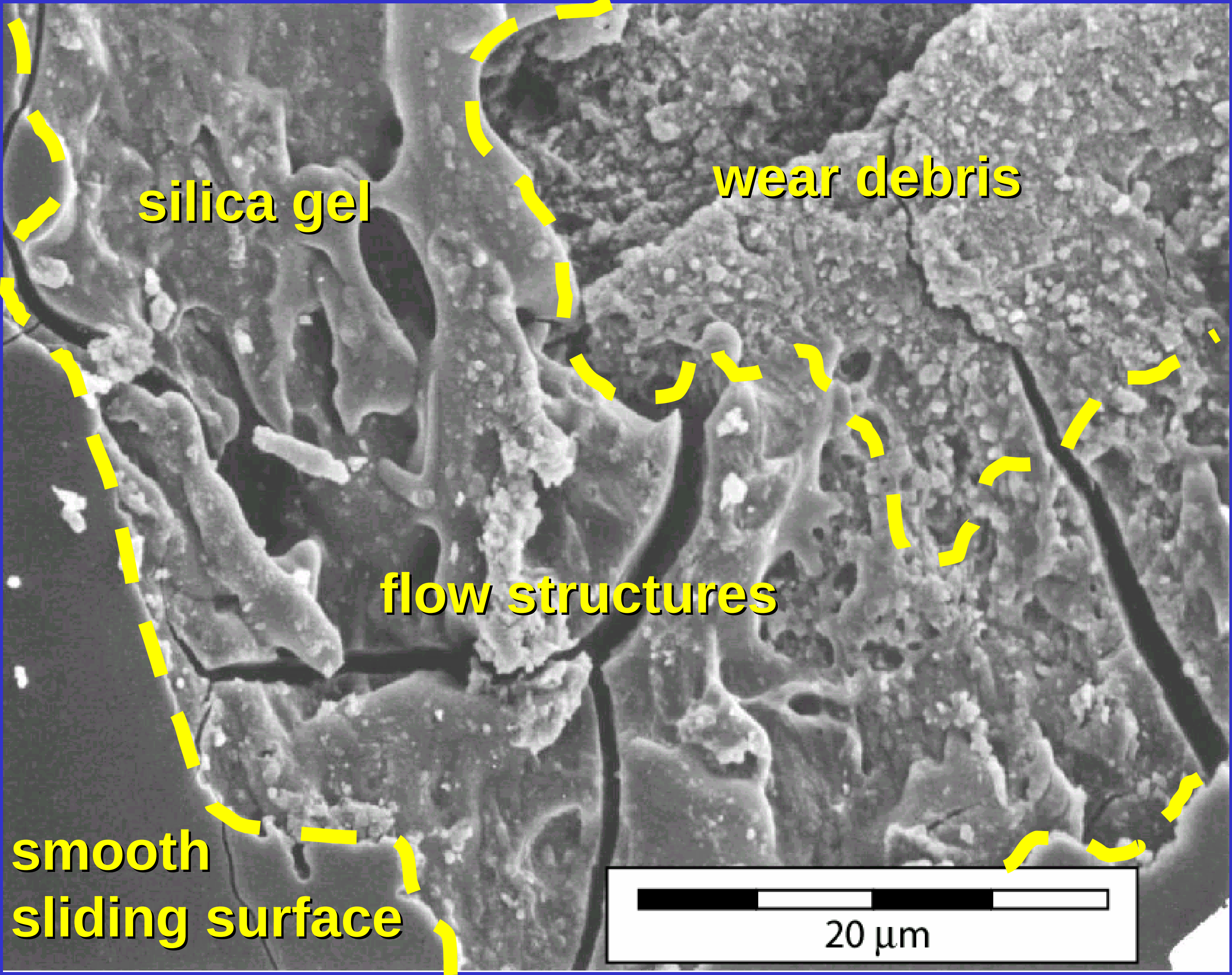
the case for melt lubrication

Novaculite (= 100% quartz) sample after the high velocity experiment

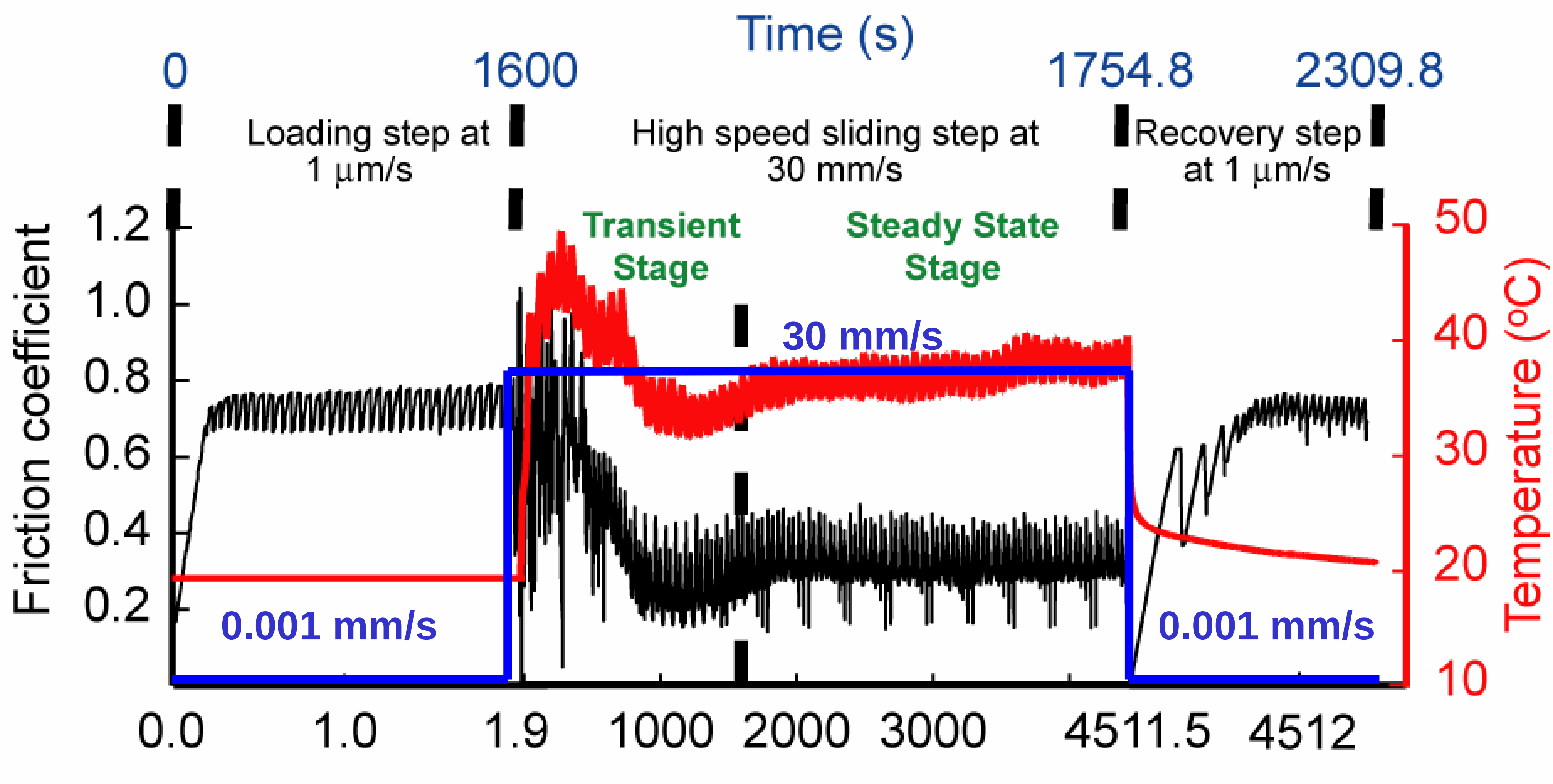
SEM image of the sliding surface after the exp.



μ and T are low during slip:

$SiO_2 + H_2O$ ✹ $SiO_2 \cdot nH_2O$

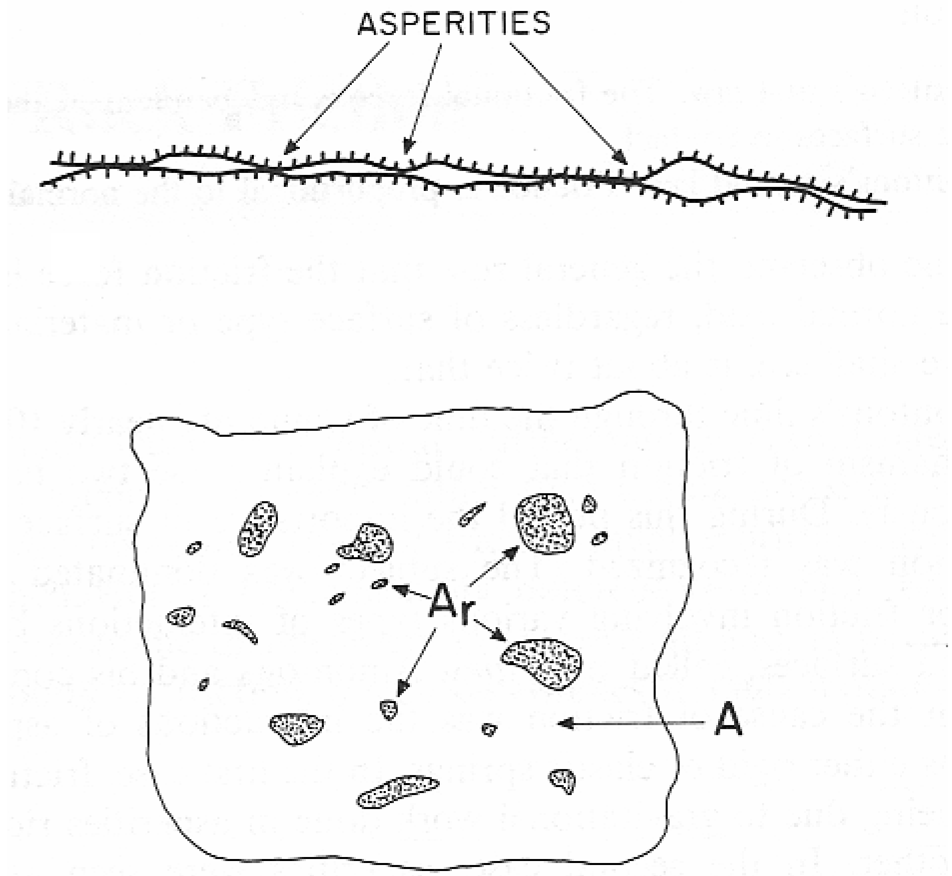
SILICA GEL LUBRICATION



Di Toro et al., Nature 2004

Flash heating at the asperity contacts

[*Archard*, 1958/59]



[*Scholz*, 1990]

$$\Delta T \cong \mu_{ss} \frac{\pi\ r\ p_m}{4K} V$$

r = 10 μm asperity radius

p_m = 8.0 GPa quartz yield press.

K = 3.8 W m^{-1} K^{-1} thermal cond.

T_{max} ~ 300 ^{o}C

Quartz melts at 1713 ^{o}C
[*Richet et al., 1982*]

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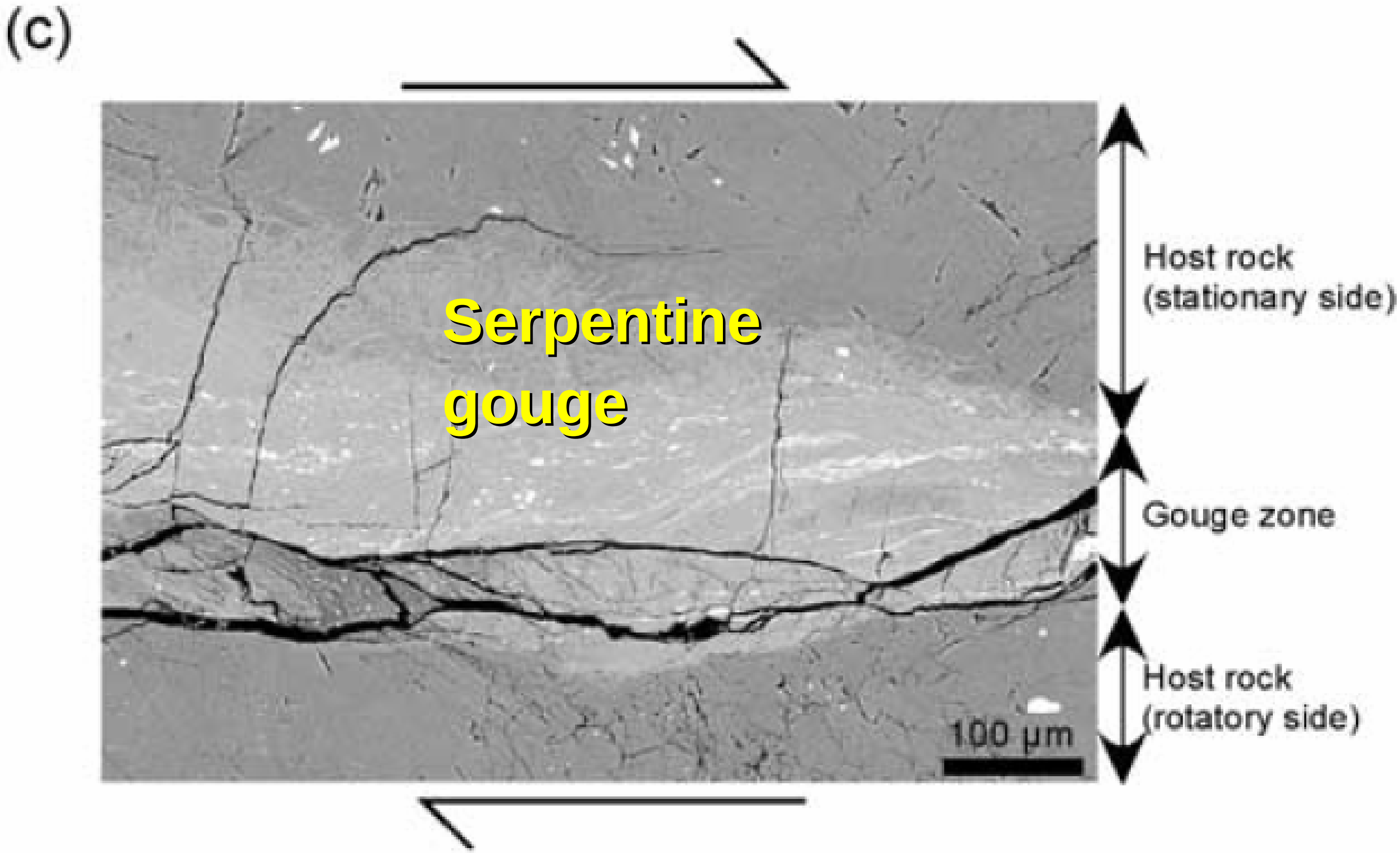
Serpentinite samples before the high-velocity exp.

Courtesy of

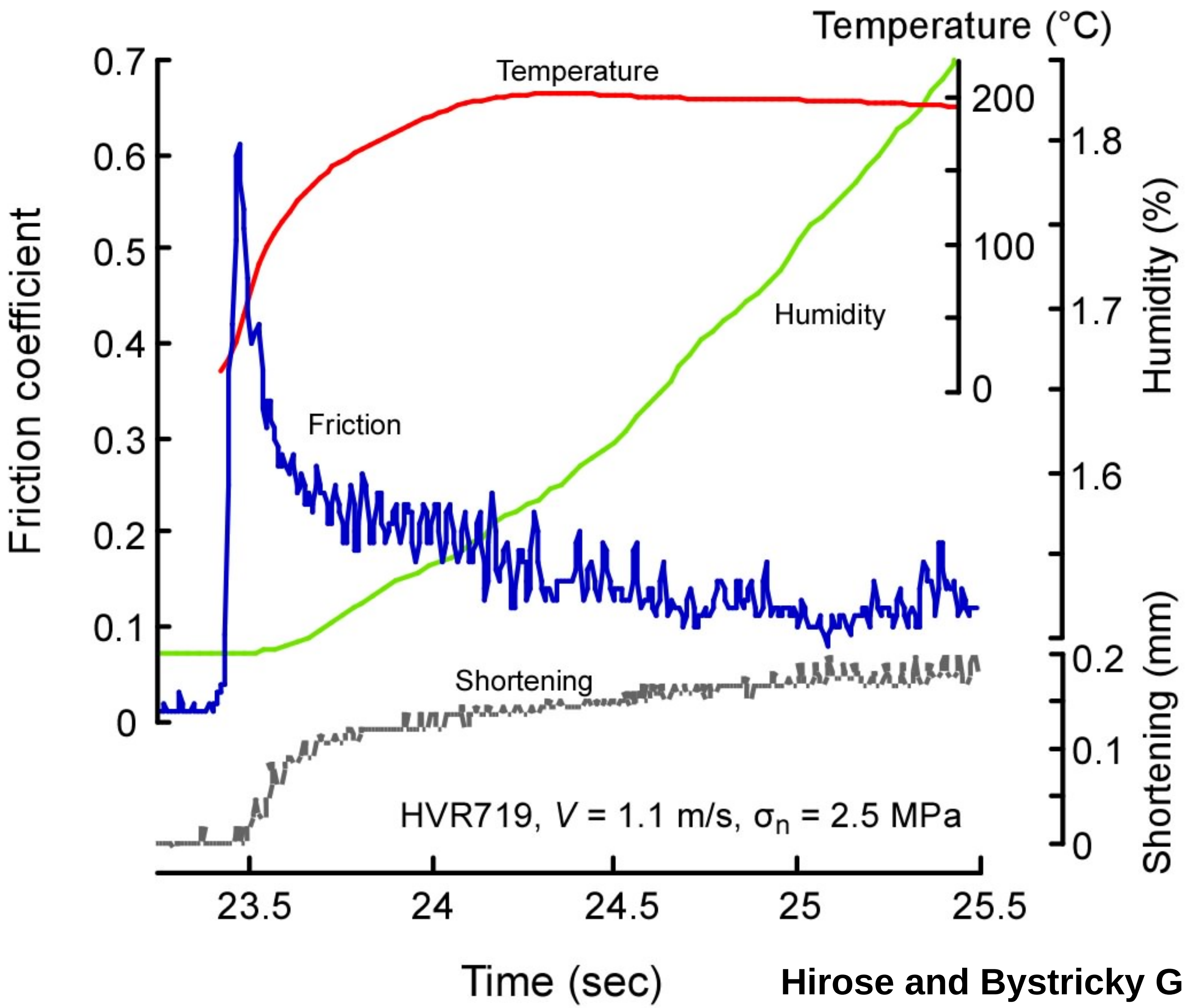
Hirose-san

SEM image of the slipping zone after the exp.



Hirose and Bystricky GRL 2007

μ is low; T increase = dehydration
DEHYDRATION INDUCED BY FLASH HEATING



Hirose and Bystricky GRL 2007

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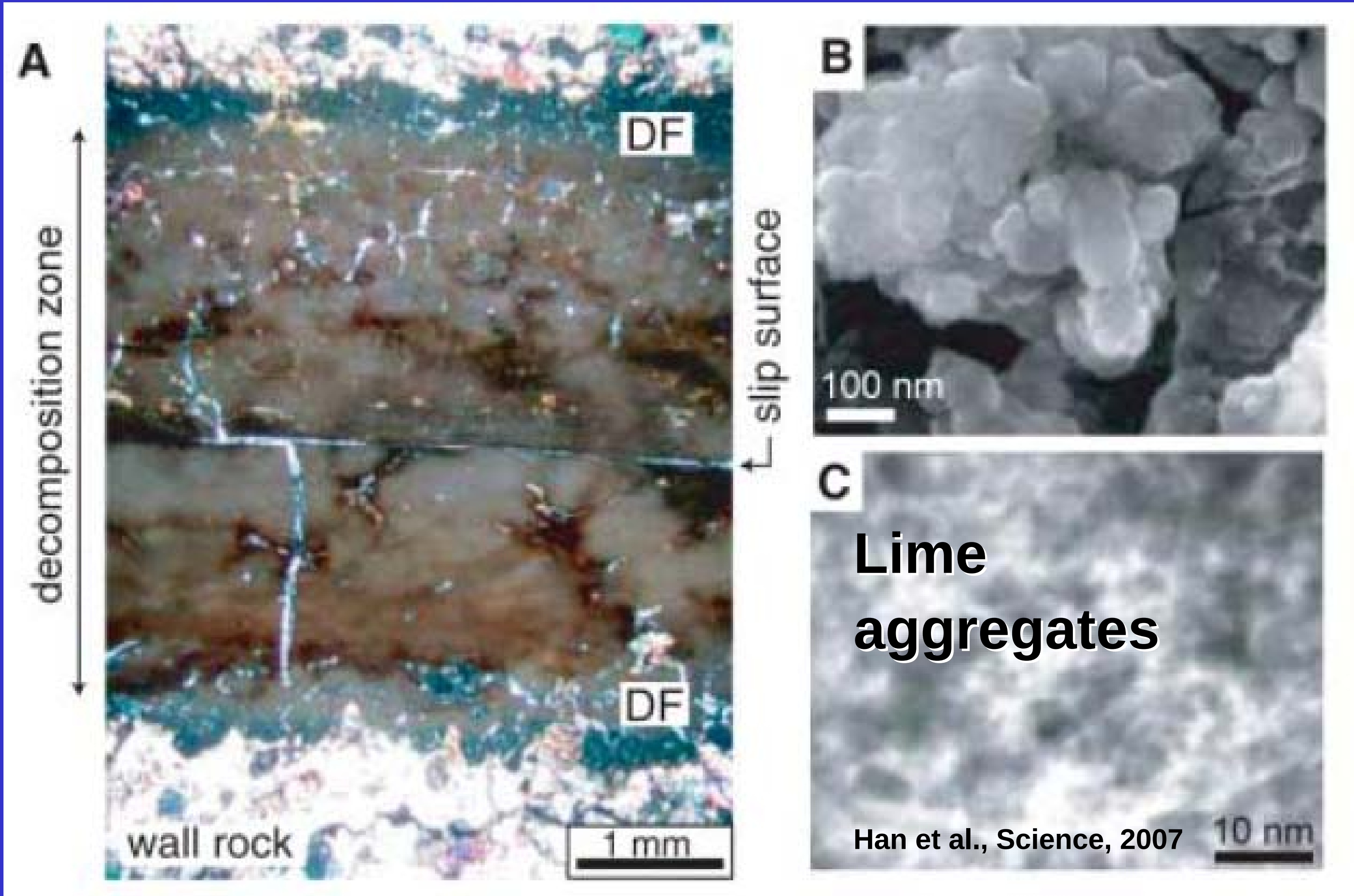
Marble sample before the high-velocity experiment

Courtesy of Raehee Han

Sample after the experiment (opt. and FE-SEM)

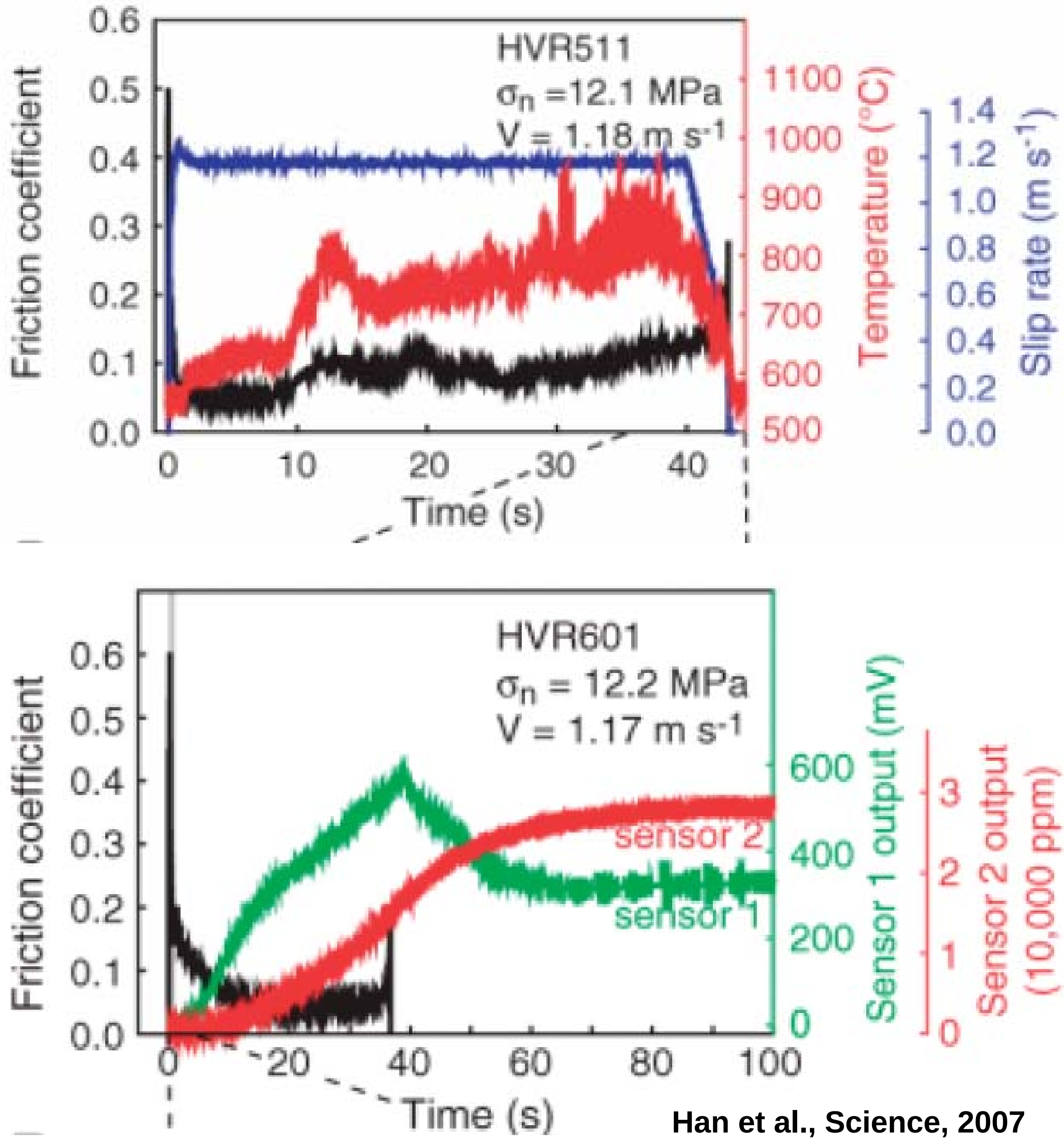
$CaCO_3$ ✸ $CaO + CO_2(g)$



Han et al., Science, 2007

μ is low,
high T
CO_2 emission:

THERMAL
DECOMP.
WEAKENING



Han et al., Science, 2007

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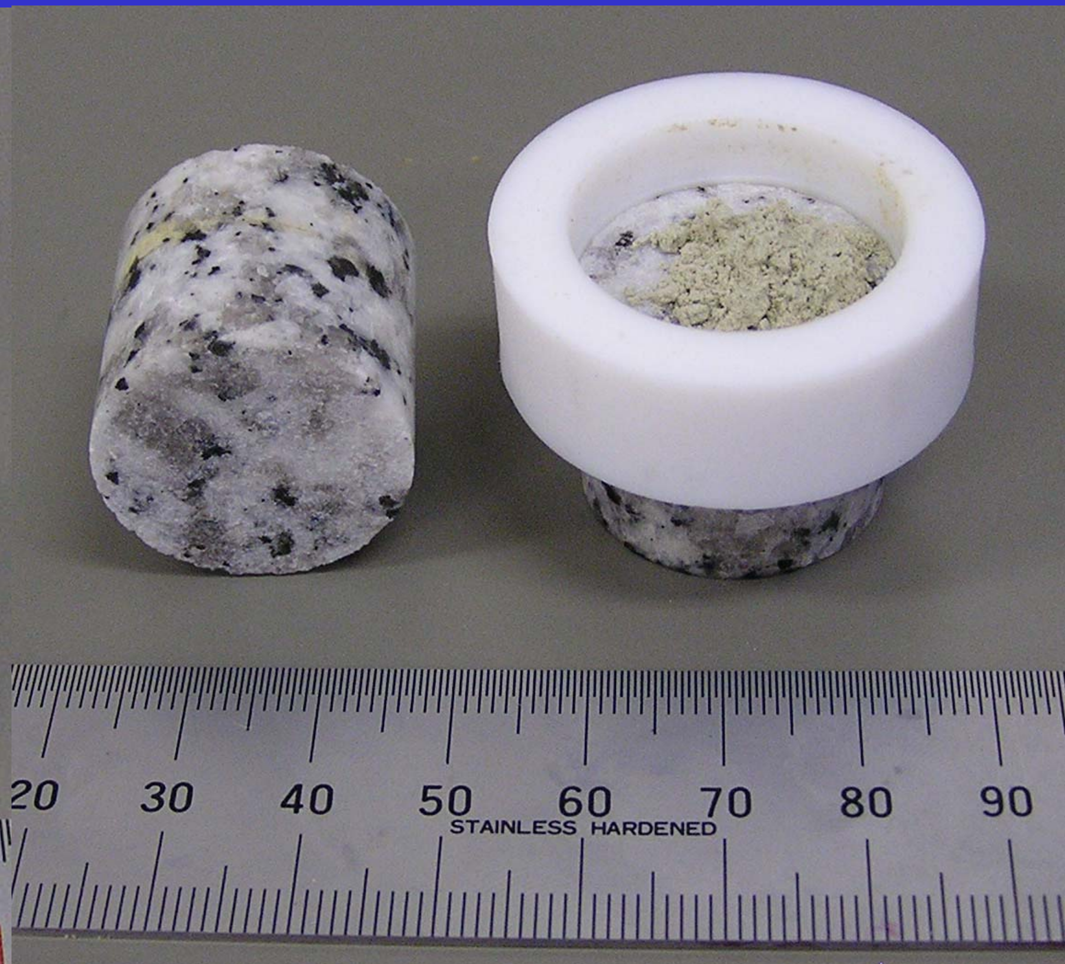
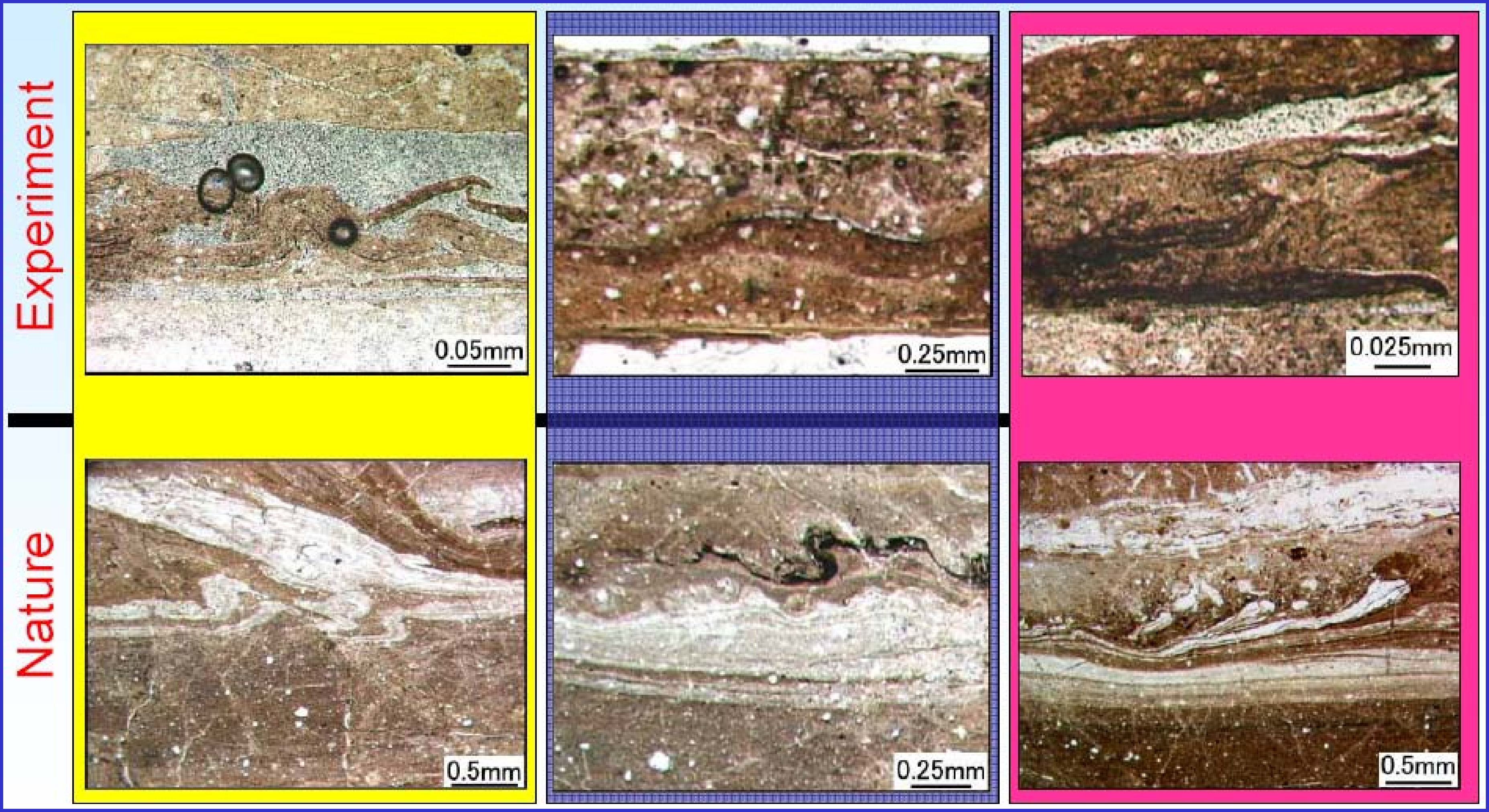
Gouge sample assembly before the experiment



Courtesy of Mizoguchi

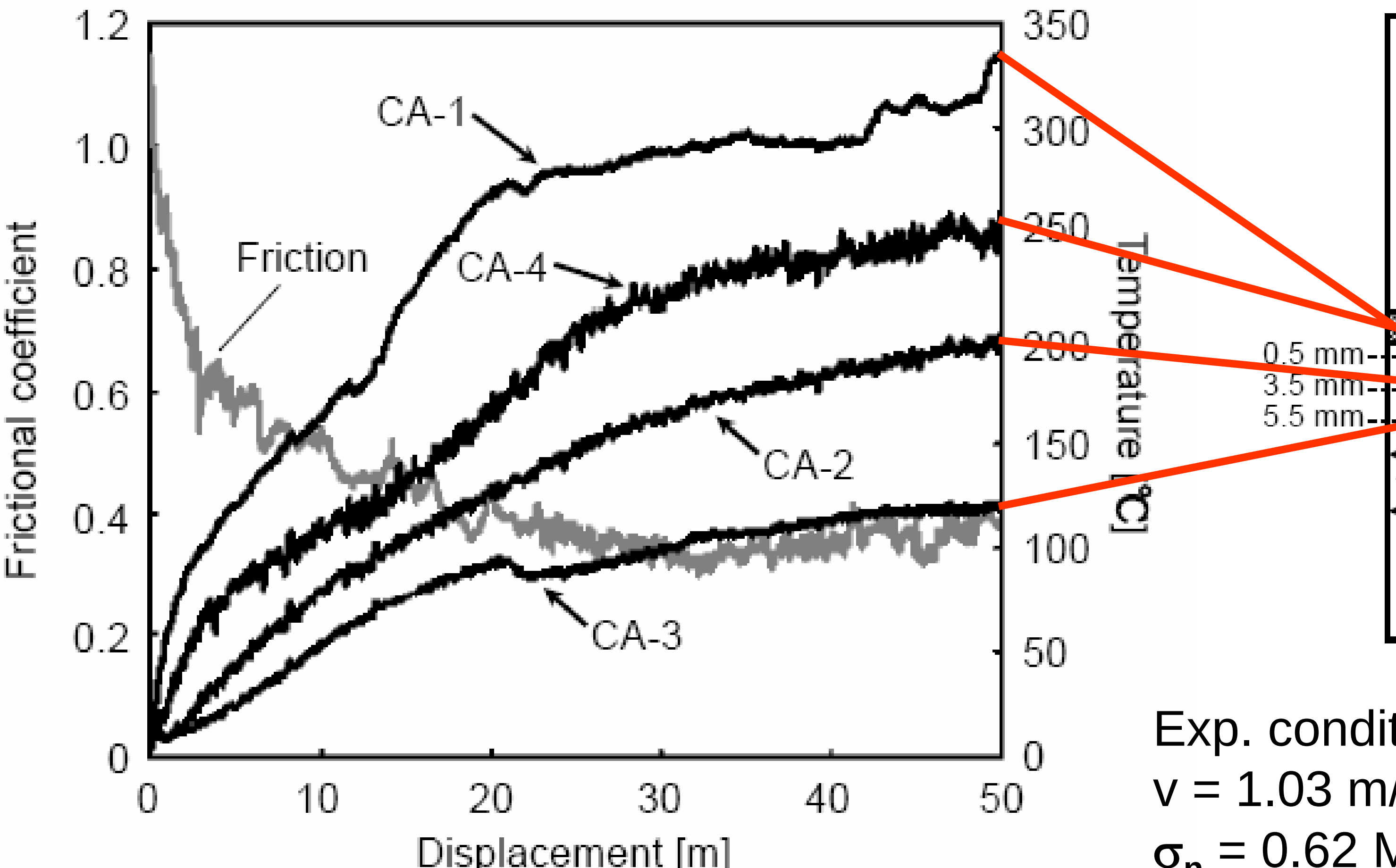
Natural and experimental fabric are very similar (under the optical microscope)



Nojima fault gouge

Mizoguchi 2005, PhD thesis

μ and T are low during slip:
GOUGE-RELATED WEAKENING

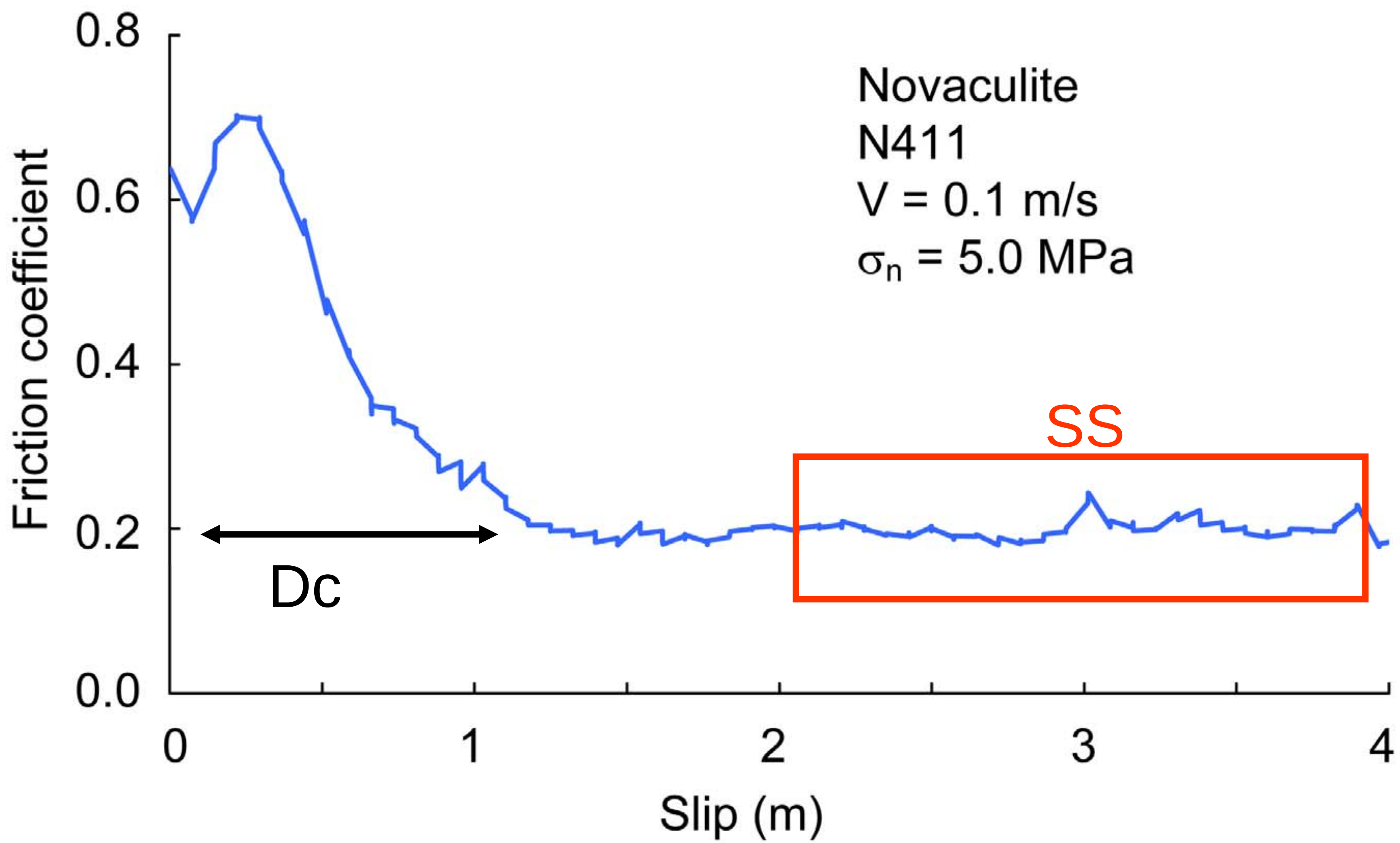


Exp. conditions
v = 1.03 m/s
σ_n = 0.62 MPa

Mizoguchi, 2005, PhD Thesis

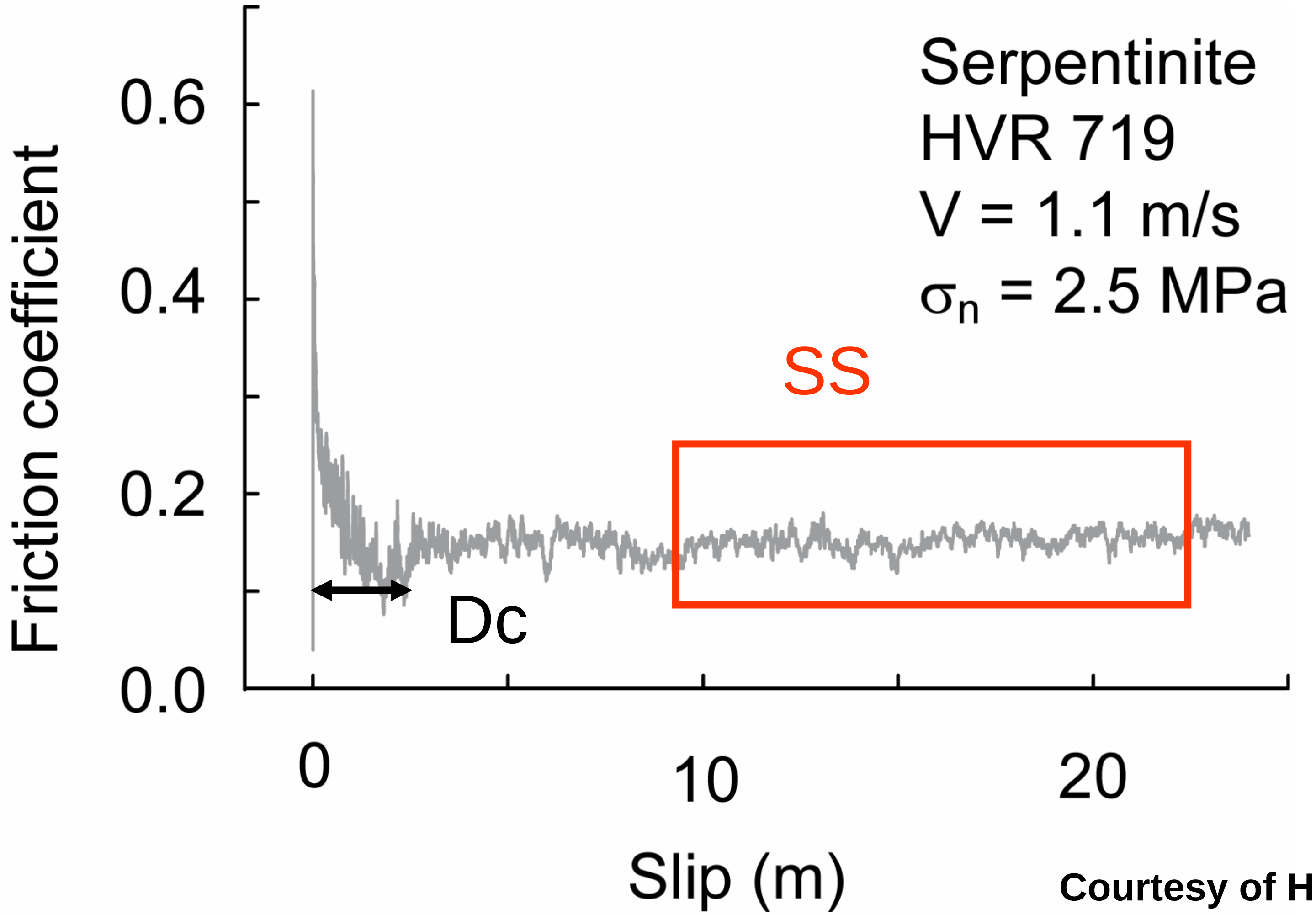
Summarizing….

Friction during silica gel lubrication: μ at steady state is ~ 0.2



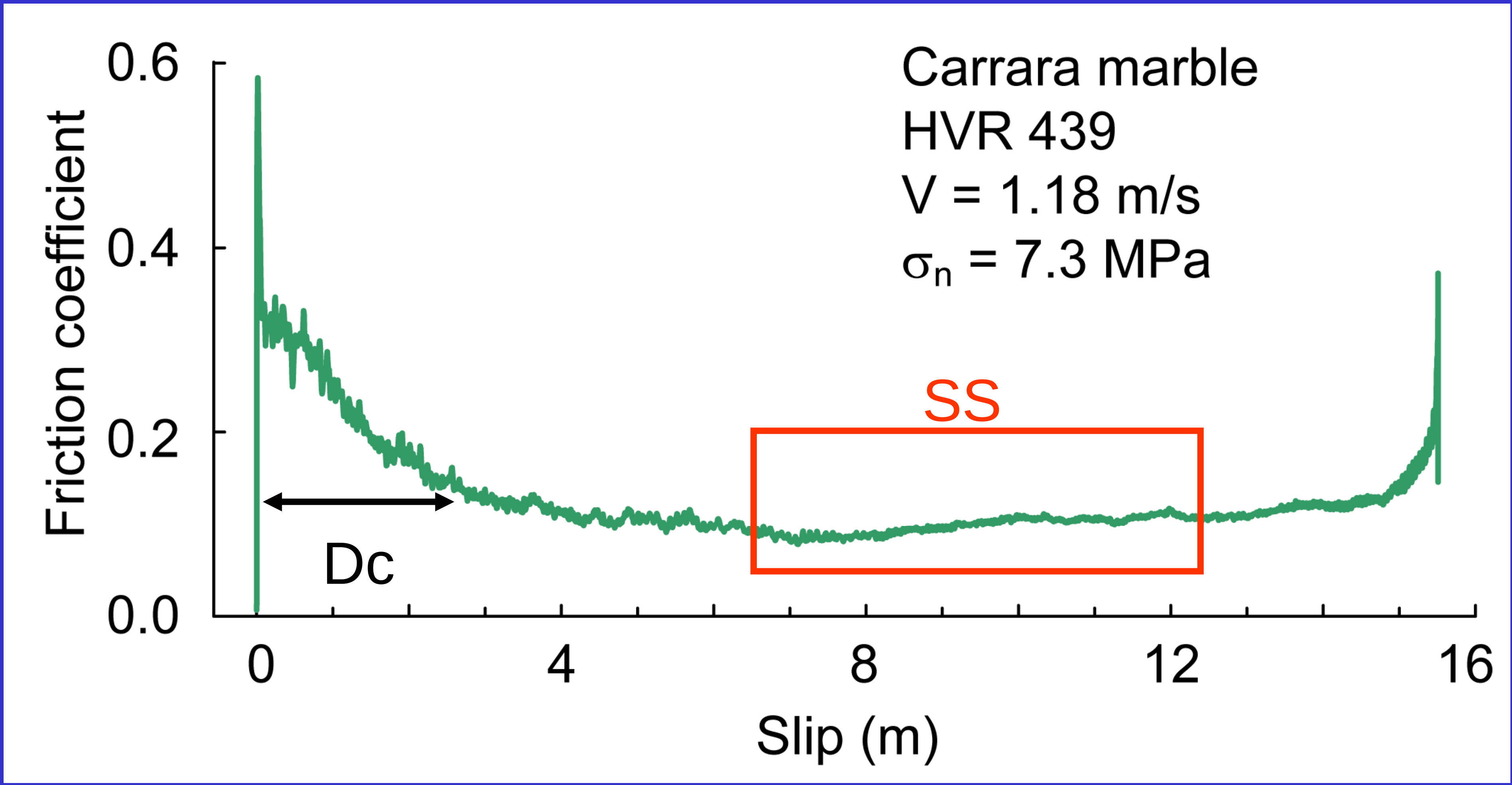
Di Toro et al., 2004

Friction during flash heating and dehydration: μ at steady state is ~ 0.15



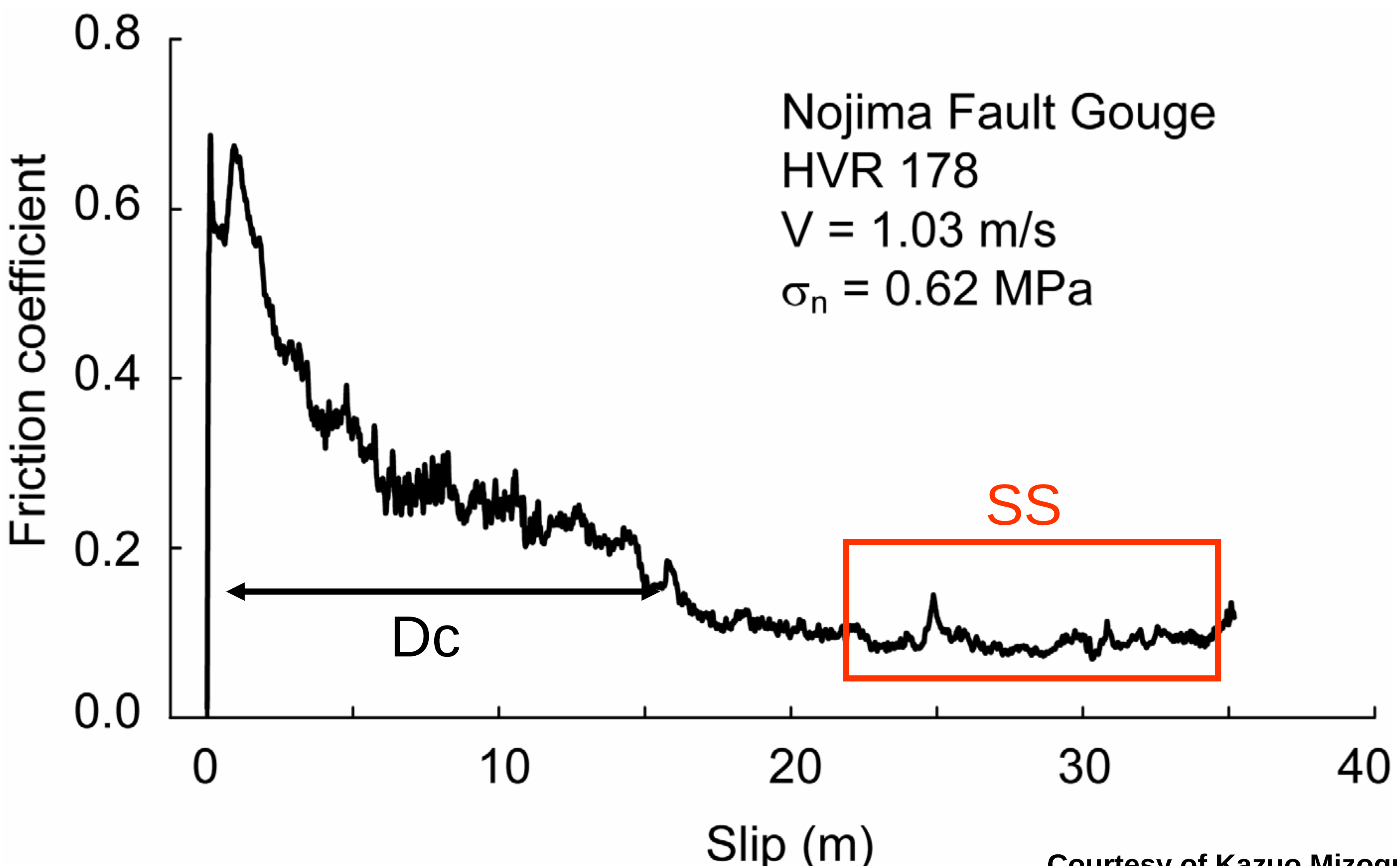
Courtesy of Hirose-san

Friction during thermal decomposition: μ at steady state is ~ 0.1



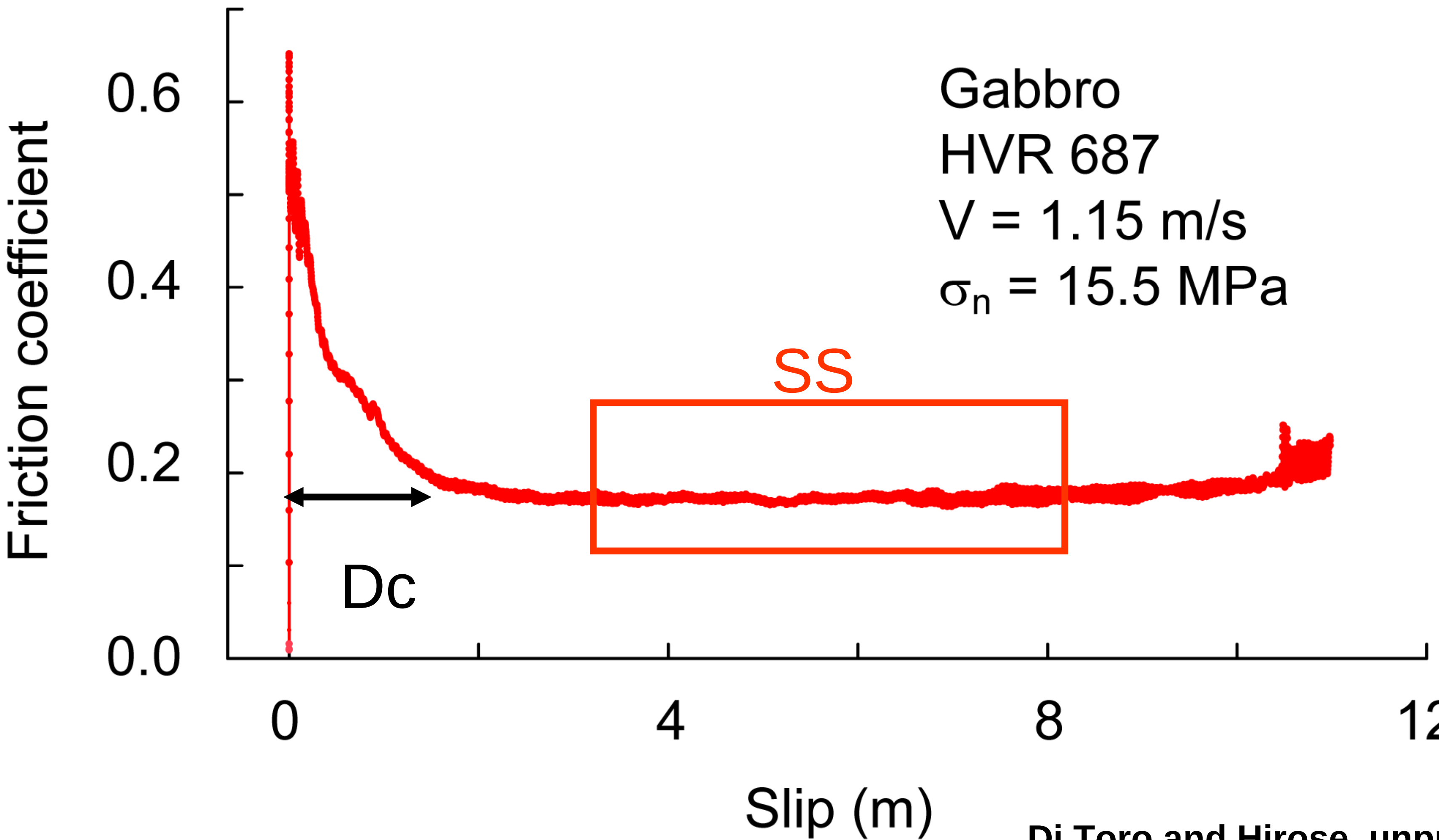
Courtesy of Raehee Han

Friction in the presence of gouge: μ at steady state is ~ 0.1



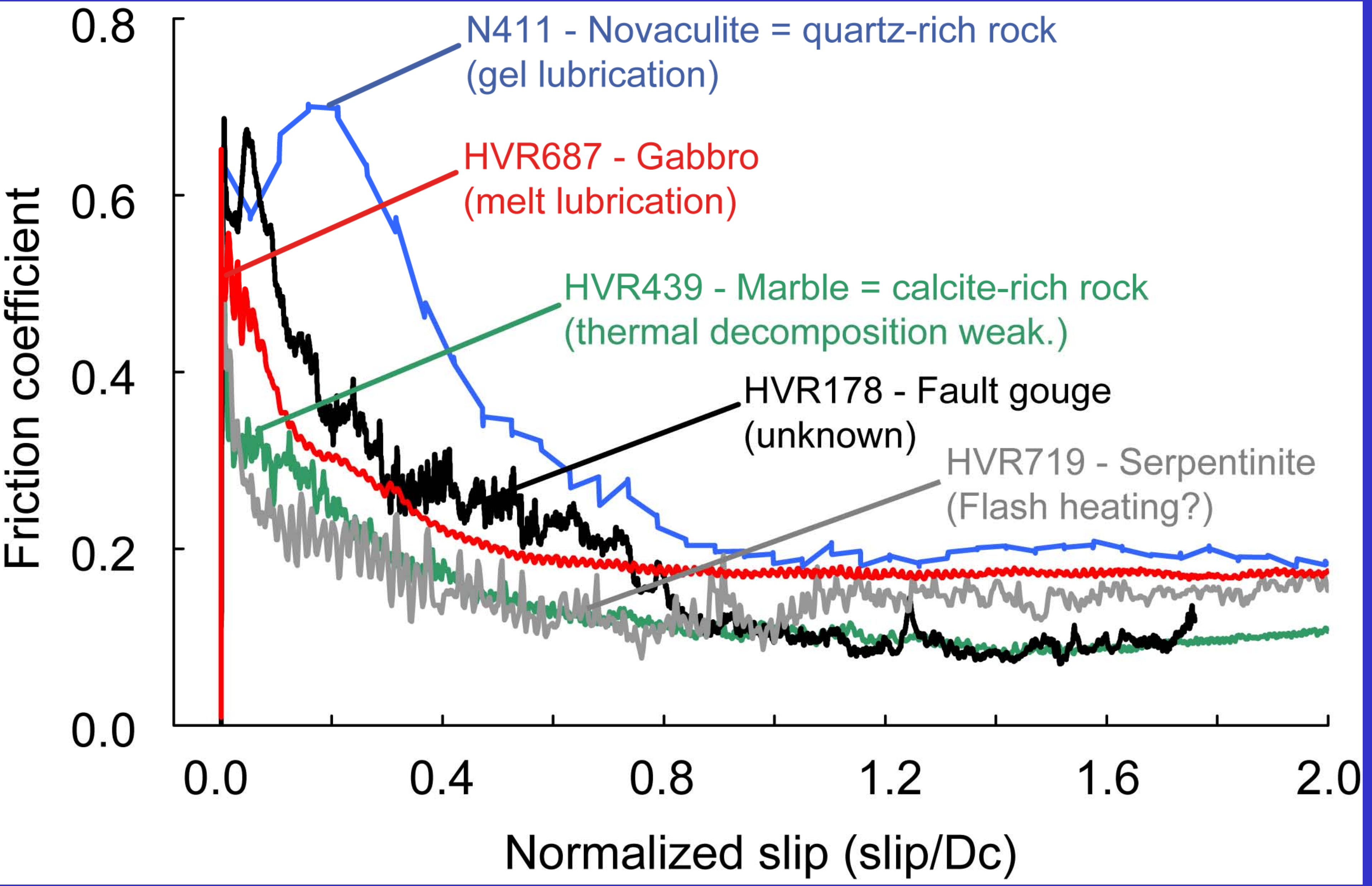
Courtesy of Kazuo Mizoguchi

Friction during melt lubrication: μ at steady state is ~ 0.2



Di Toro and Hirose, unpubl.

HVRFE = **low friction at seismic slip rates**



Outline

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2. High-velocity rock friction experiments (HVRFE)

    2a. Silica gel lubrication
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    2c. Thermal decomposition weakening
    2d. Gouge-related weakening

3. Extrapolation of experimental data to seismic slip: the case for melt lubrication

Extrapolation of experimental data to seismic slip: melt lubrication

1) Pseudotachylytes (solidified seismic melts) are unambiguously recognized as EQ scars **(Cowan, JSG, 1999)**.

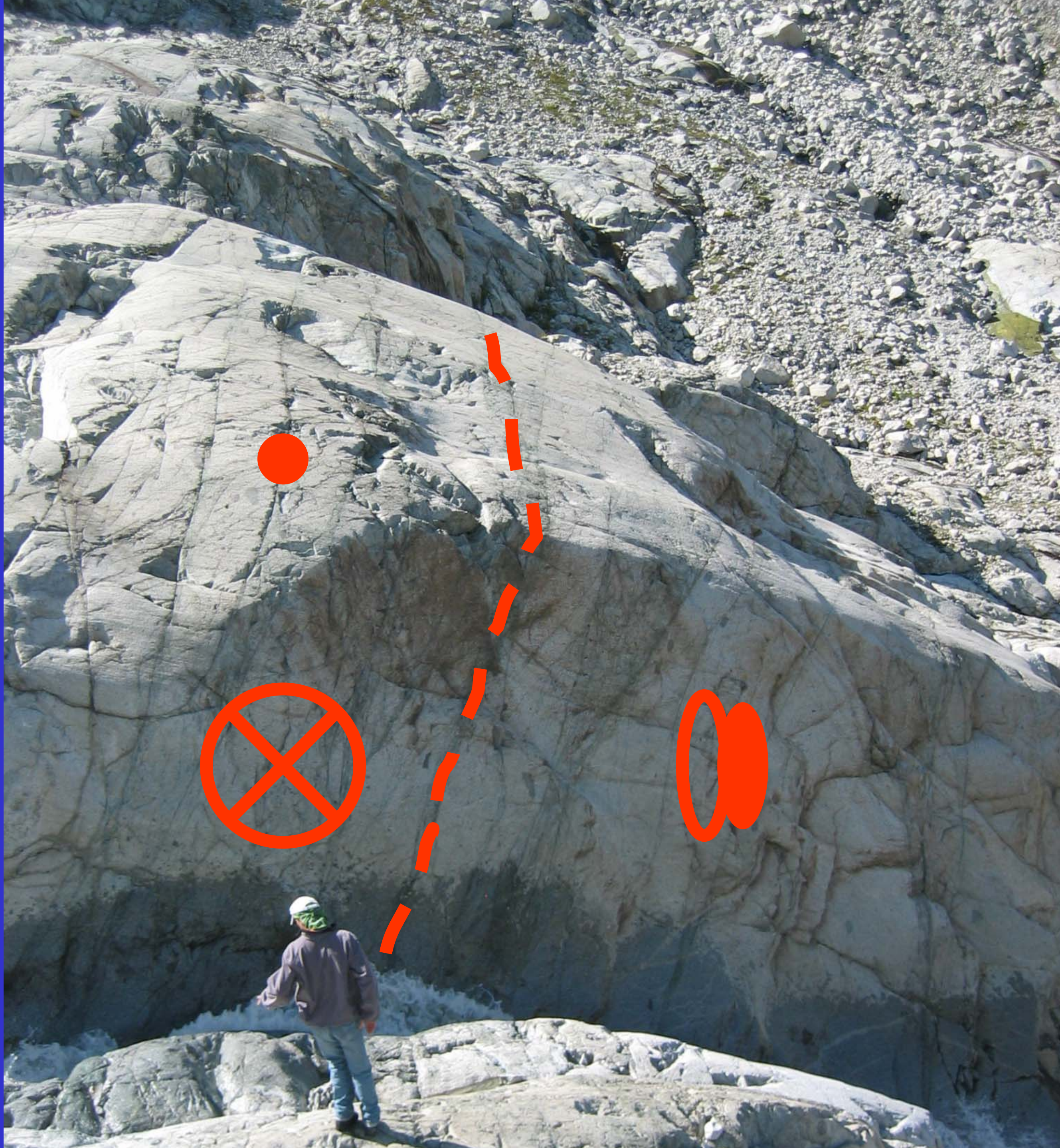
2) Pseudotachylytes allow to determine dynamic fault strength from exhumed faults **(Di Toro et al., Tectonophysics, 2005)**

3) Experimental solidified melts products are almost identical to natural pseudotachylytes **(e.g., Spray, Geology, 1995)**.

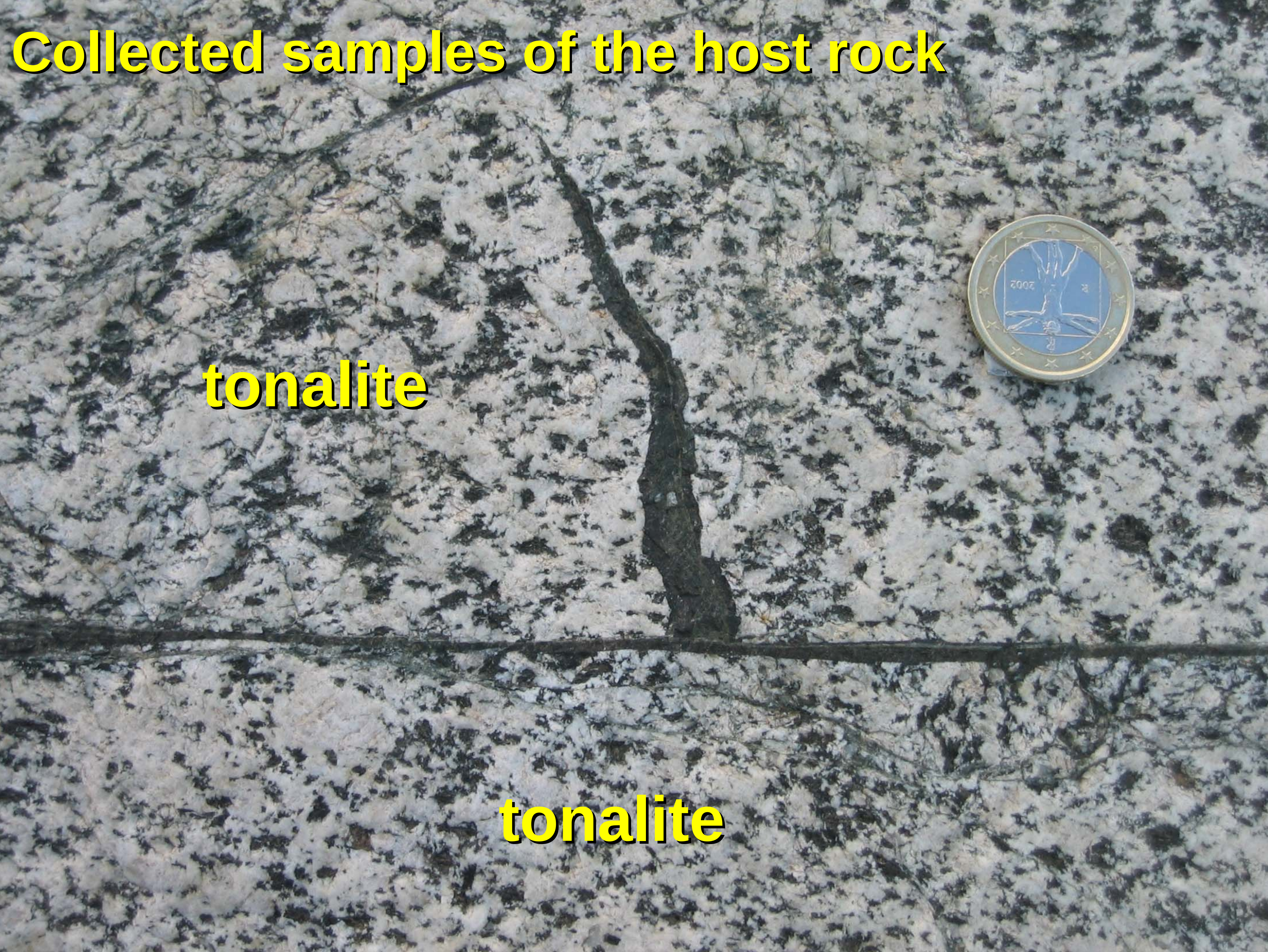
4) Theoretical analysis is simpler (!?) than for any other weakening mechanism **(Fialko and Khazan, JGR, 2005)**.

PST-bearing faults exhumed from 10 km depth.

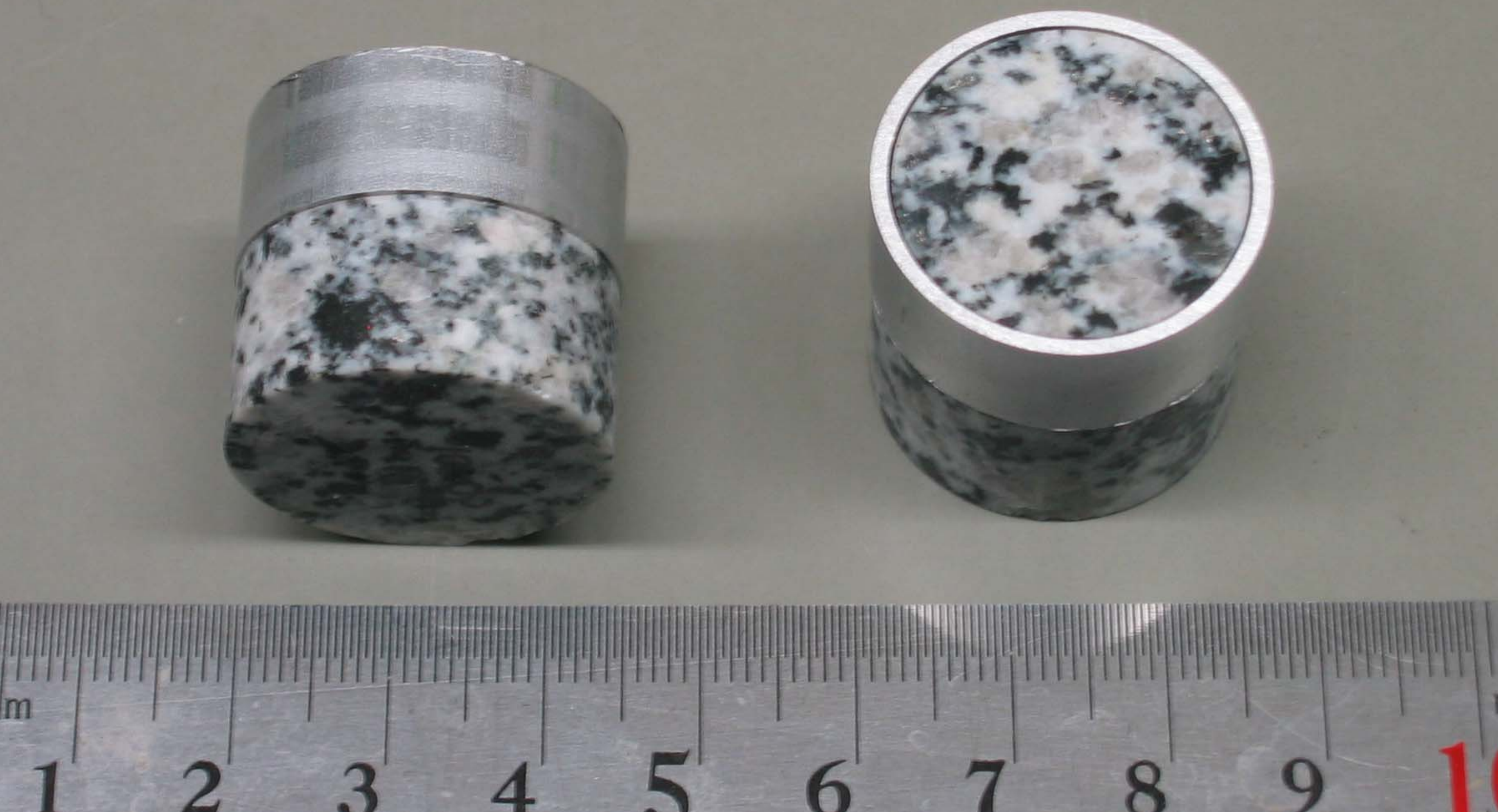
(Adamello, Italy)



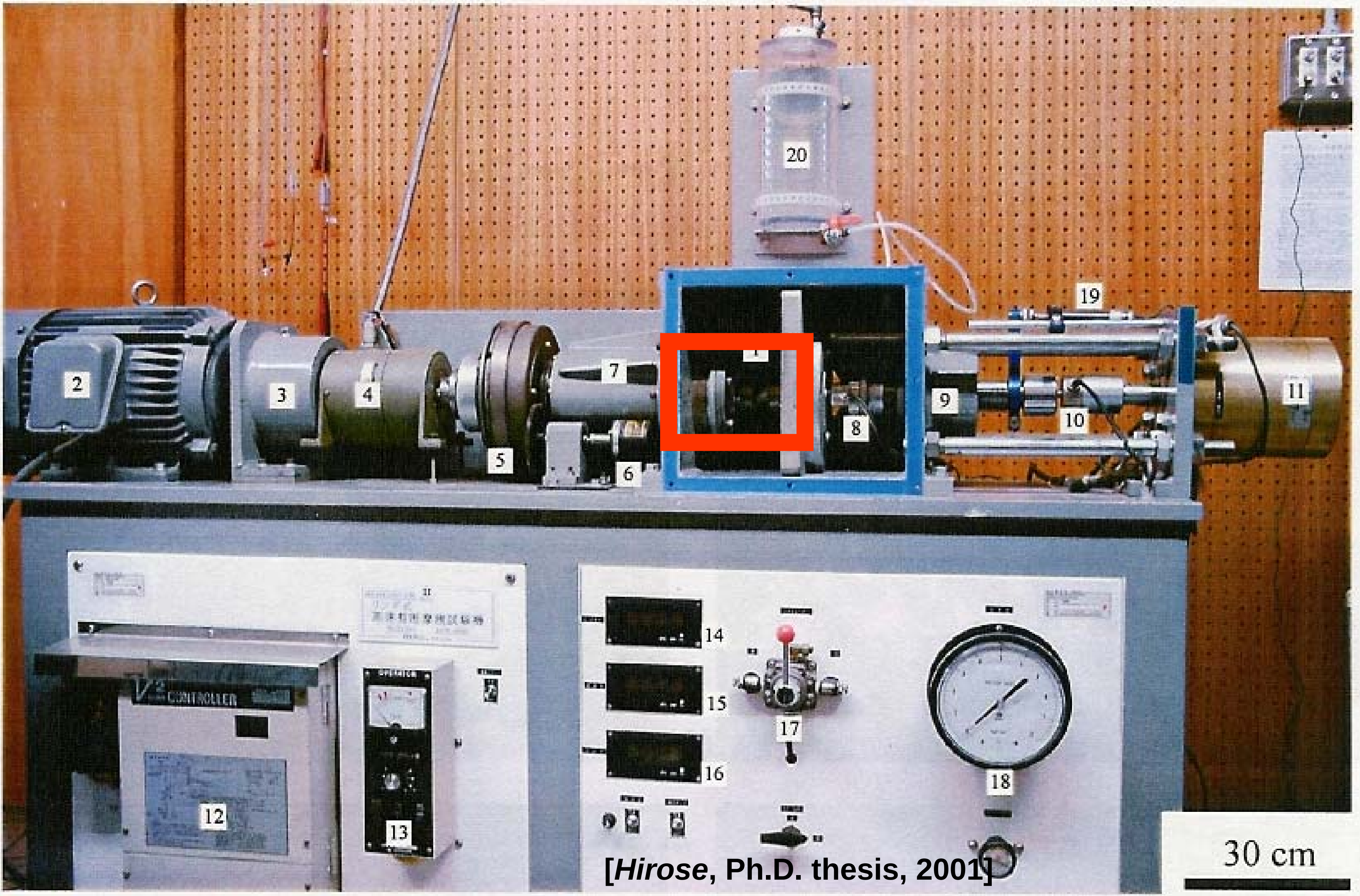
[*Di Toro and Pennacchioni*, JSG, 2004]


Collected samples of the host rock
tonalite
tonalite

…prepared samples…



…run experiments

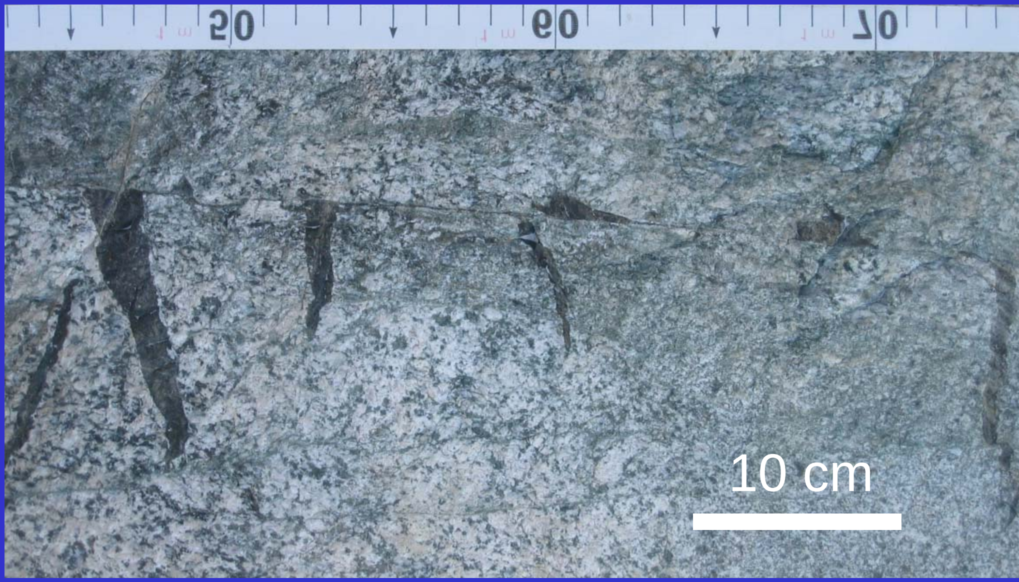


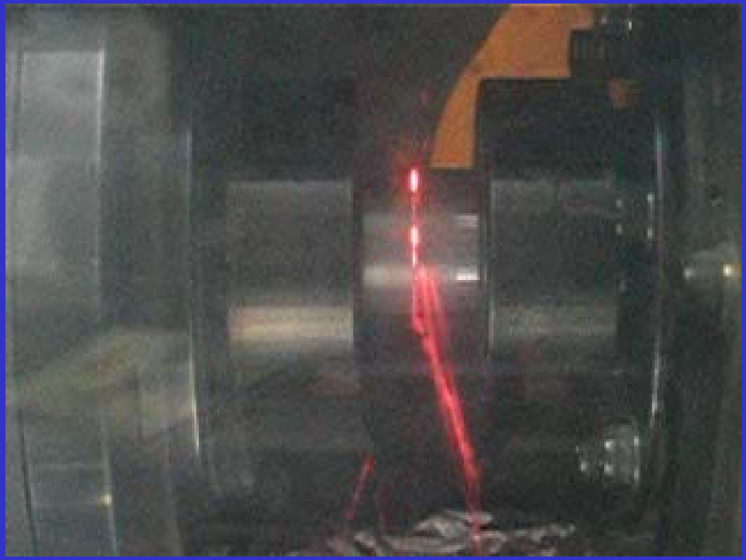
[*Hirose*, Ph.D. thesis, 2001]

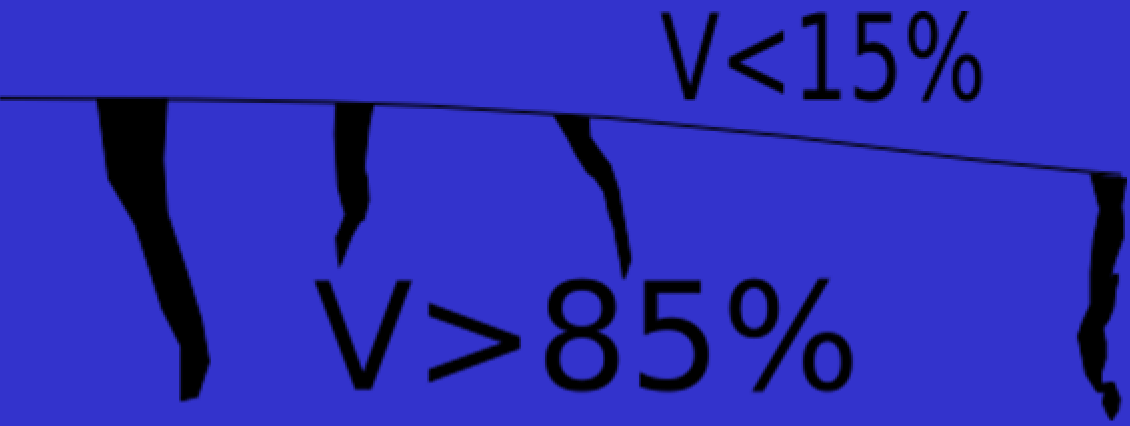
Tonalite, v = 1.3 m/s, σ_n = 20 MPa

20 mm

Melt extrusion in nature and experiments



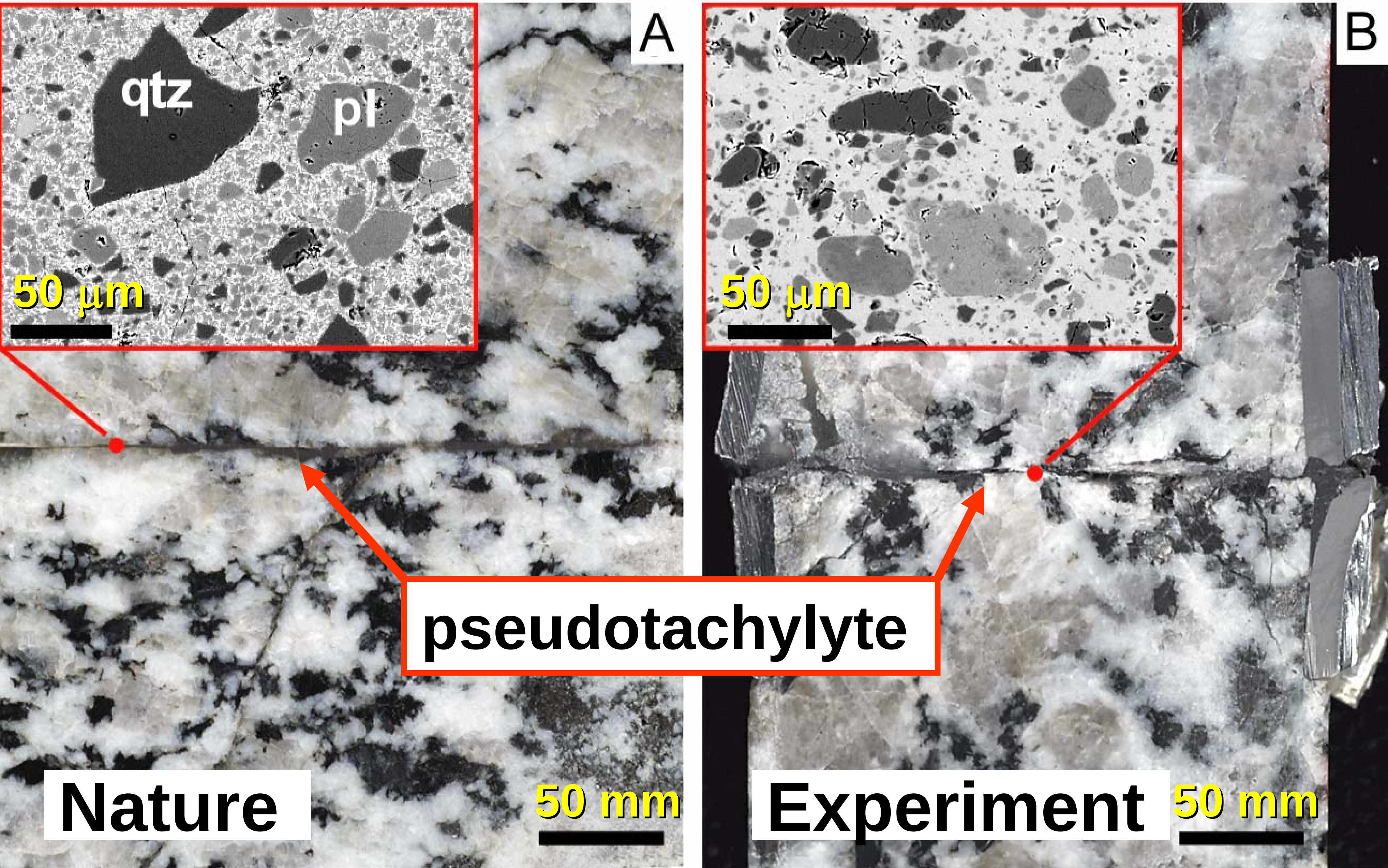




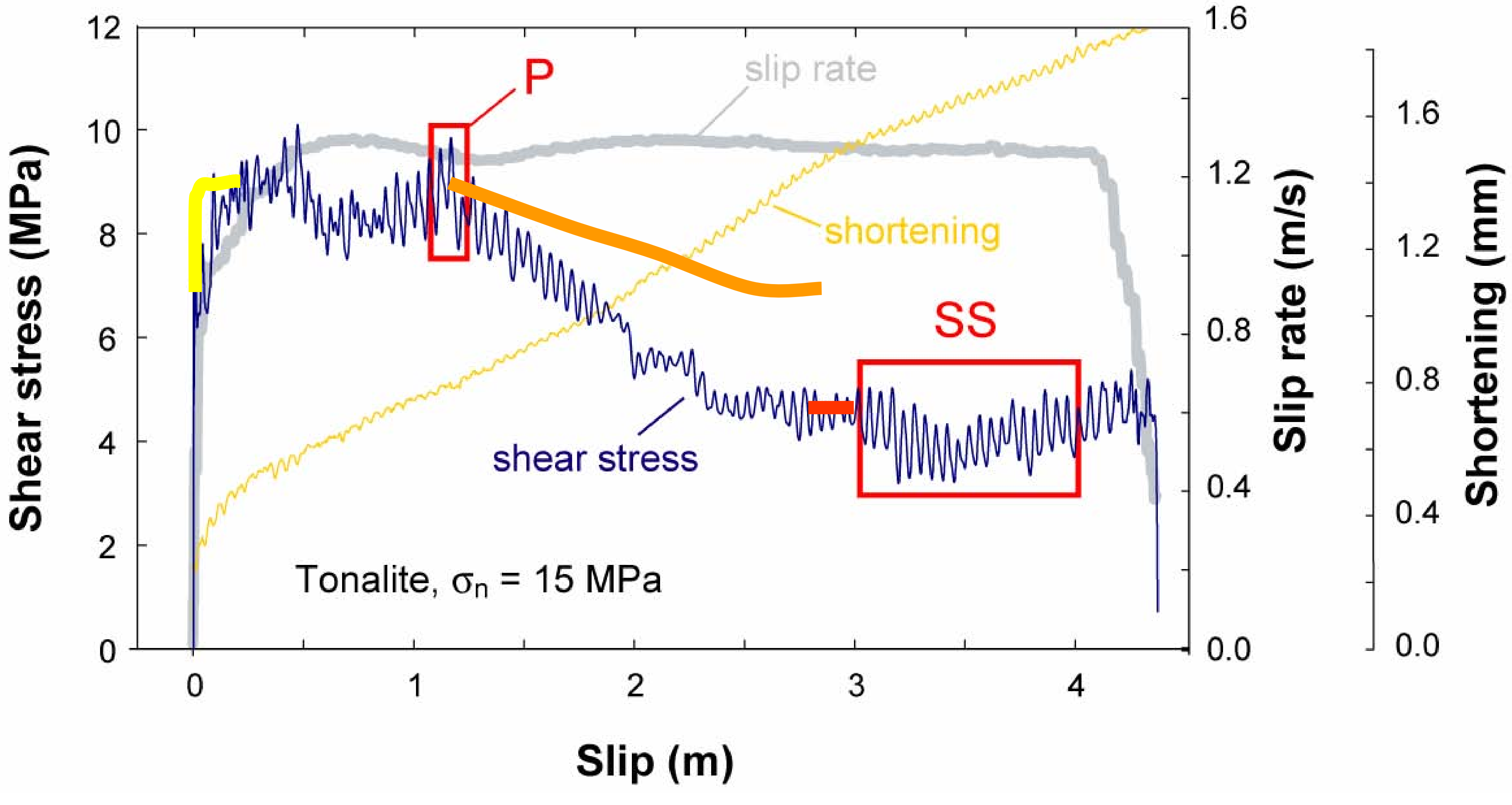
Nature

Experiment

Natural and experimental microstructures are very similar (also under SEM)

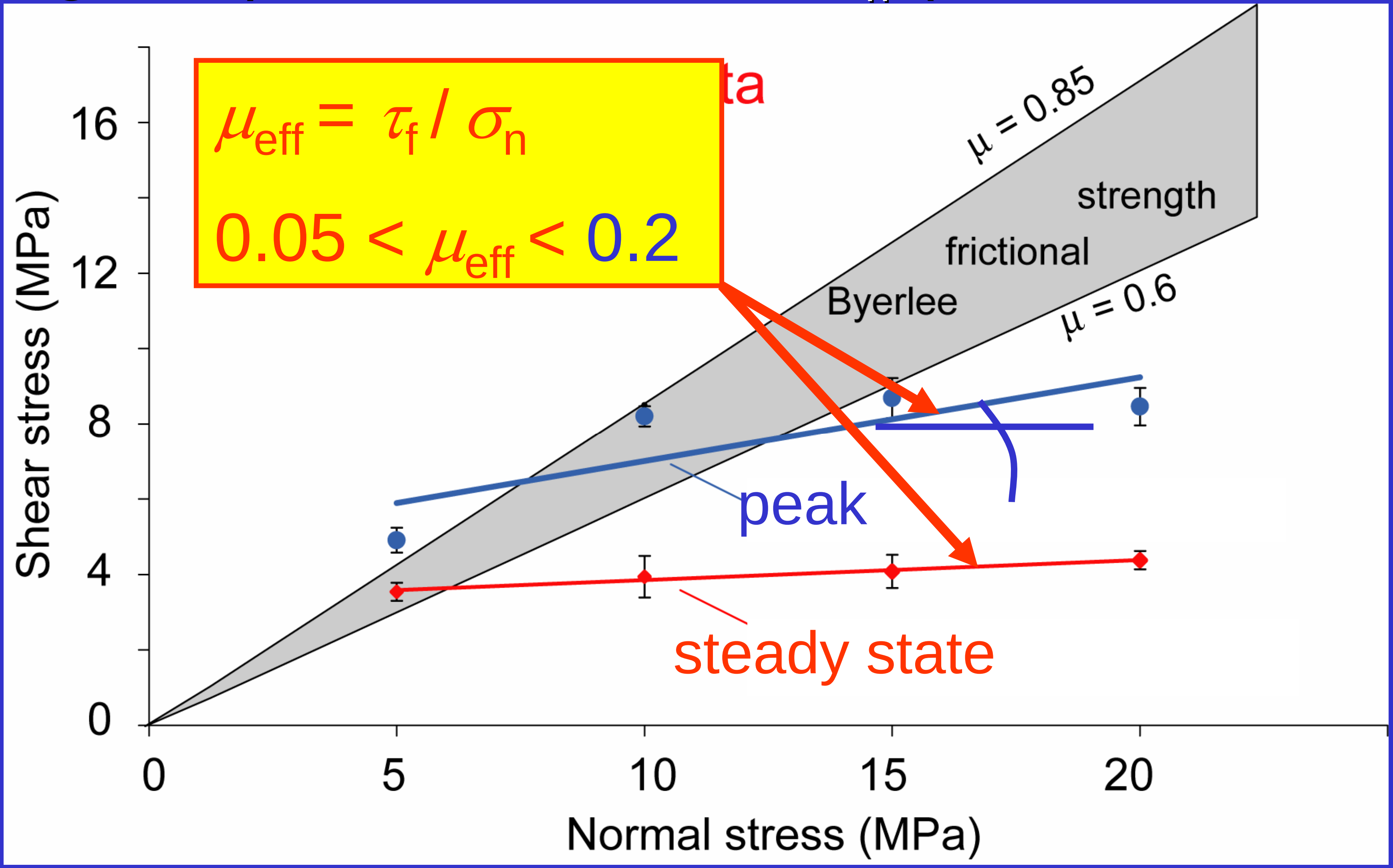


Traction evolution: 1. strengthening stage
2. transient stage
3. steady state stage

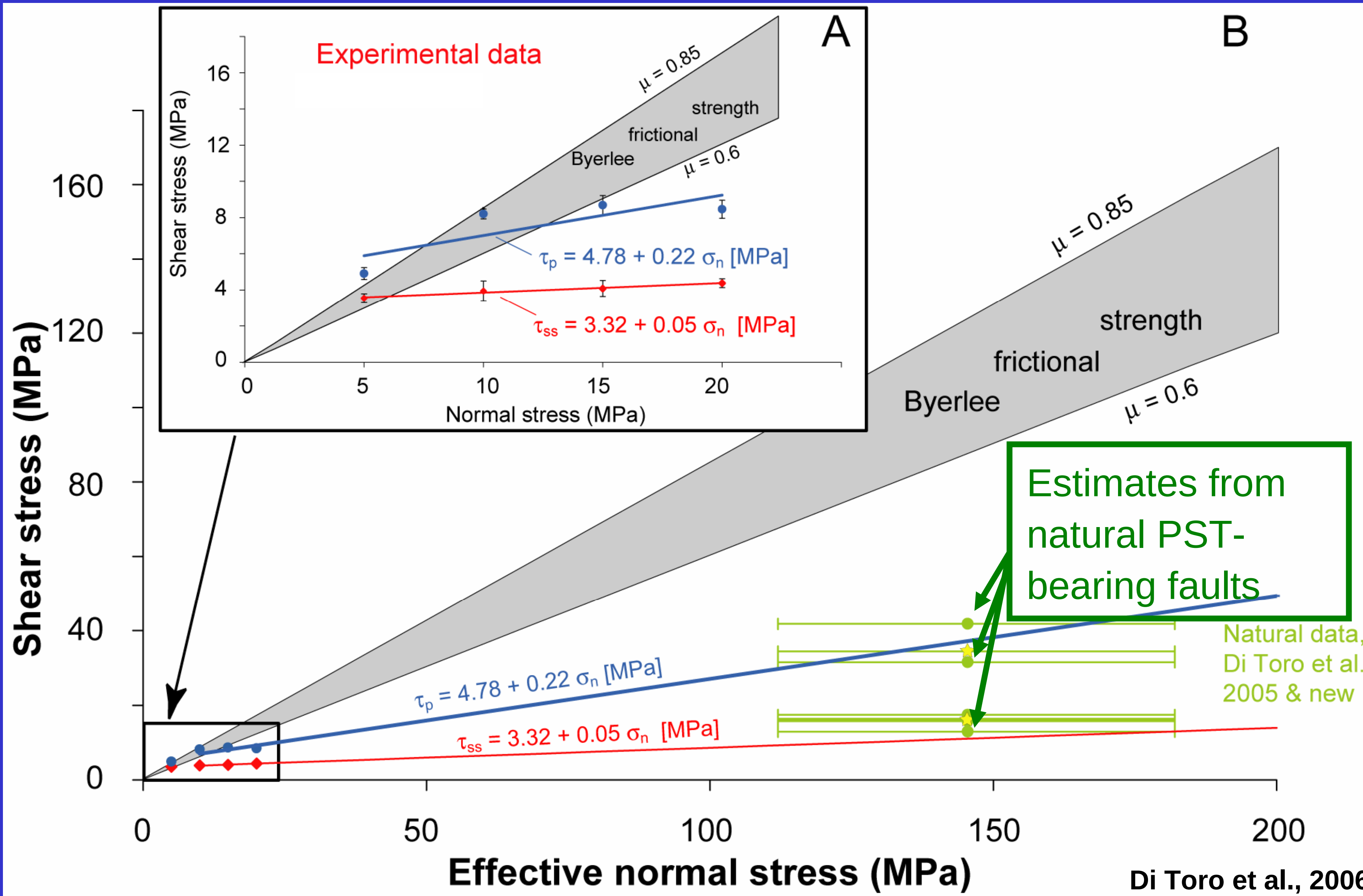


By performing several exp. with increasing σ_n

- **low strength** in the presence of melt
- slight dependence of τ with σ_n (**melt lubrication**)



Melt lubrication in experiments and nature



Di Toro et al., 2006

This is a poor extrapolation

The **effective friction coefficient** does not fit the “physics”: no solid friction here.

Melt lubrication is the result of

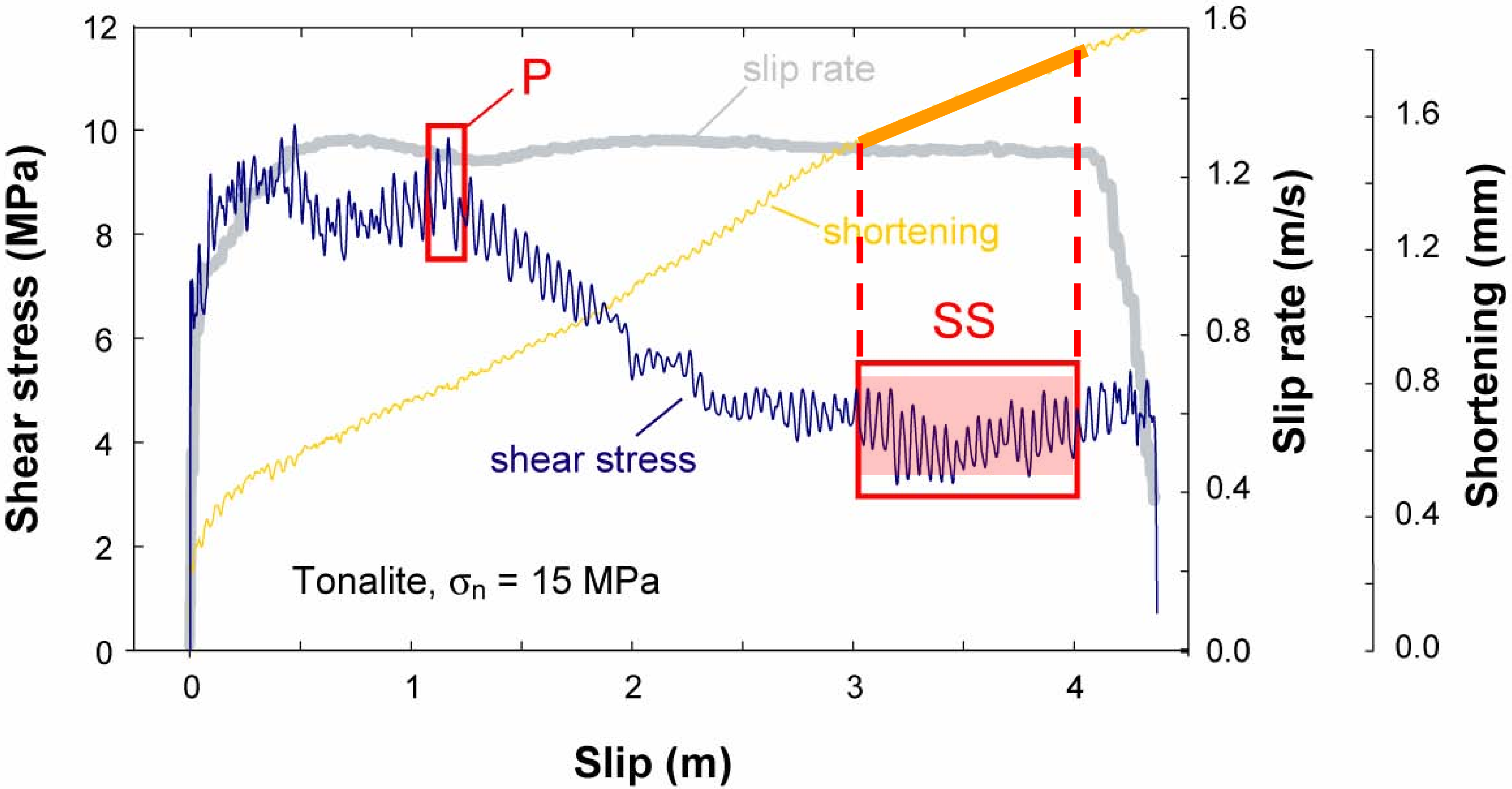
melt temperature
melt composition
clast and bubble content

melt viscosity
melt layer thickness
strain rate
melt extrusion

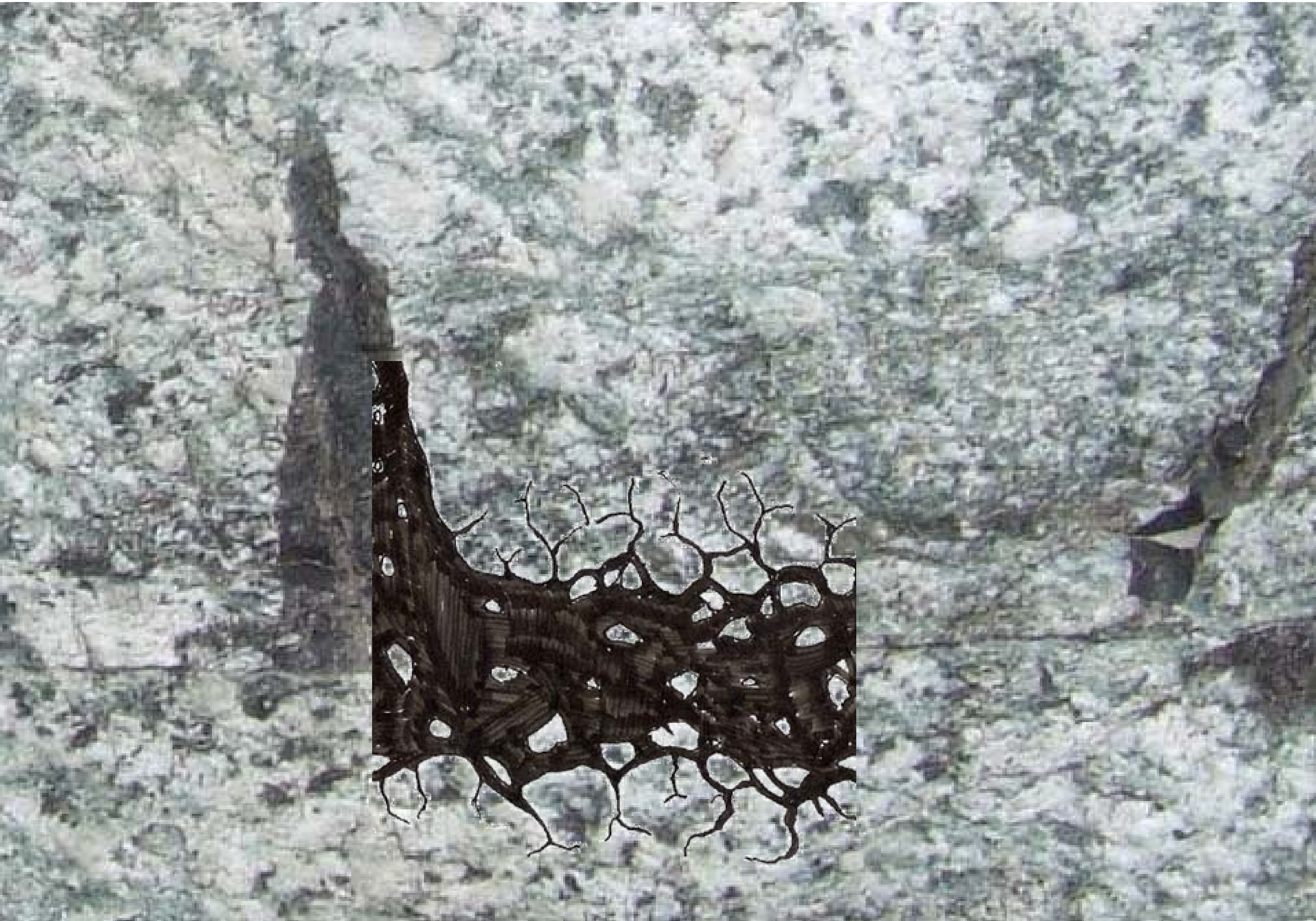
MELT VISCOSITY

MELT LUBRICATION

A **constitutive equation** for melt lubrication.
Let's focus on the **steady state** stage.
Here the **shortening rate** is constant.

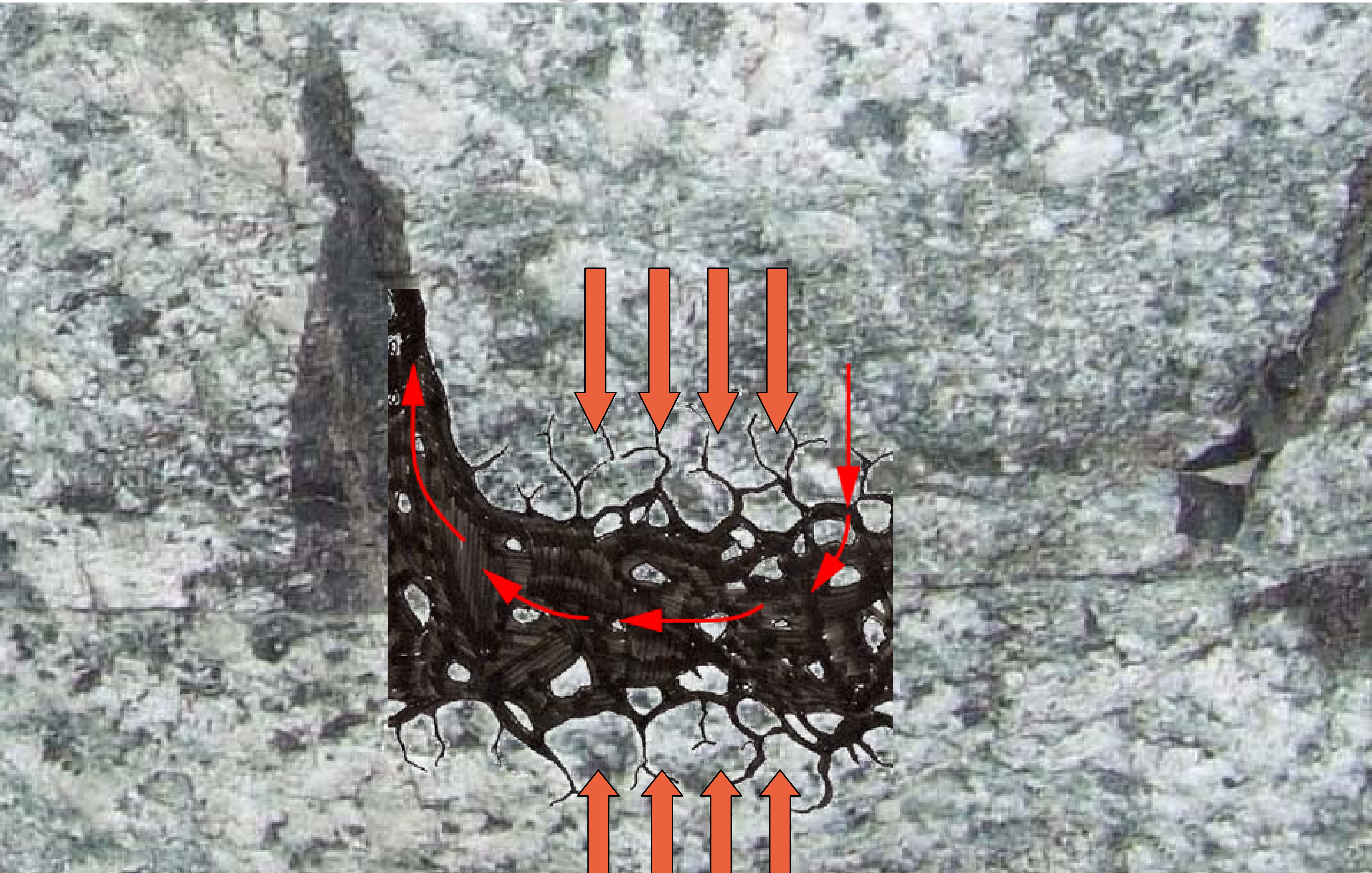


Modelling steady-state: a complex world

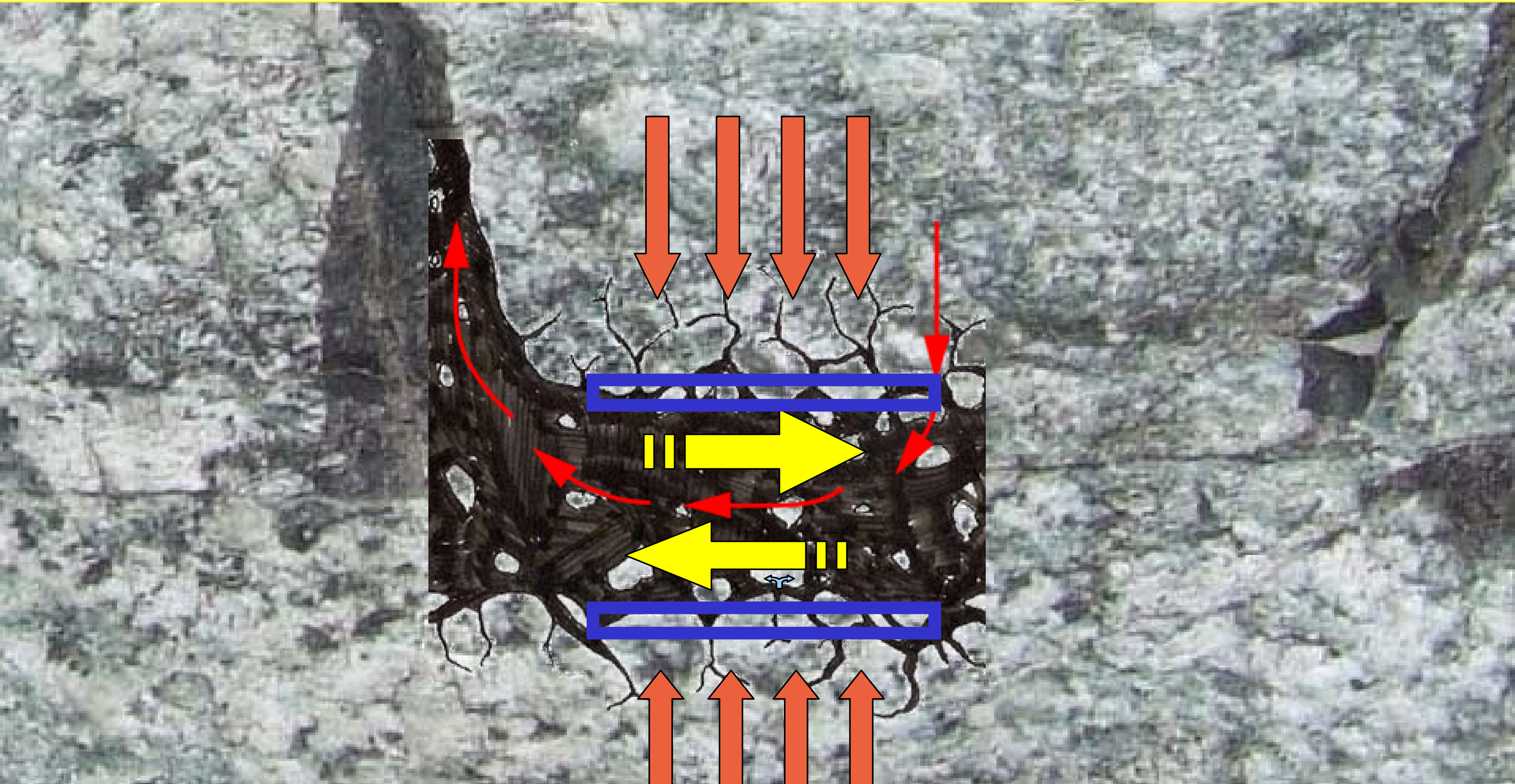


melt thickness is constant (Hirose and Shimamoto, 2005)

melting-, shortening-, melt extrusion-rate = cst



melt thickness is constant (Hirose and Shimamoto, 2005)
melting-, shortening-, melt extrusion rate = cst.
heat produced by viscous flow & shear heating
latent heat of fusion = heat loss by melt extr.



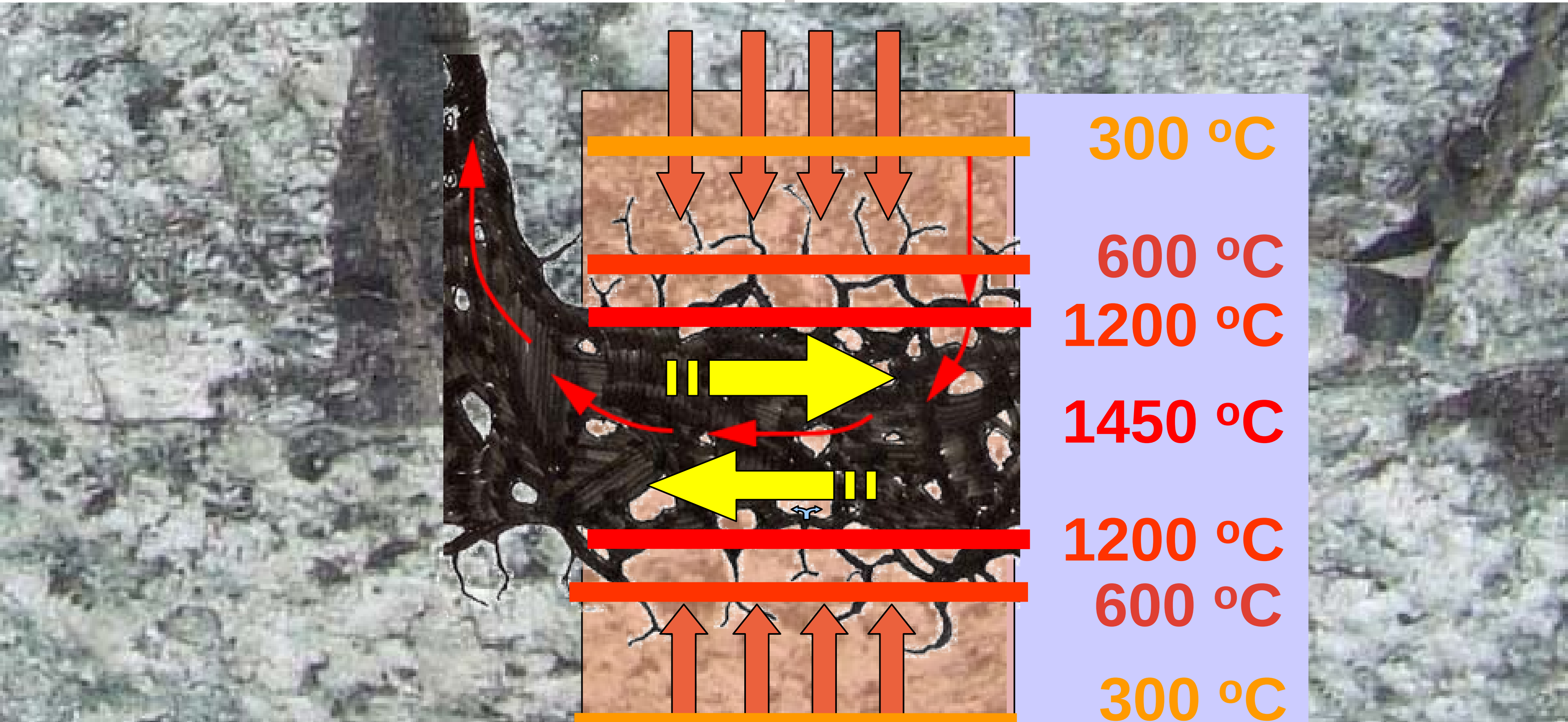
melt thickness is constant (Hirose and Shimamoto, 2005)

Melting-, shortening-, melt extrusion-rate = cst

heat produced by viscous flow & shear heating

latent heat of fusion = heat loss by melt extr.

isotherms are fixed in space and time



System of **five coupled equations**:

1) Melt/solid interface: Stefan problem

2) Solid host rock: heat diffusion

3) Melt layer: shear heating

4) Extrusion: viscous flow and cooling

5) Hydrodynamic pressure

The solution is:

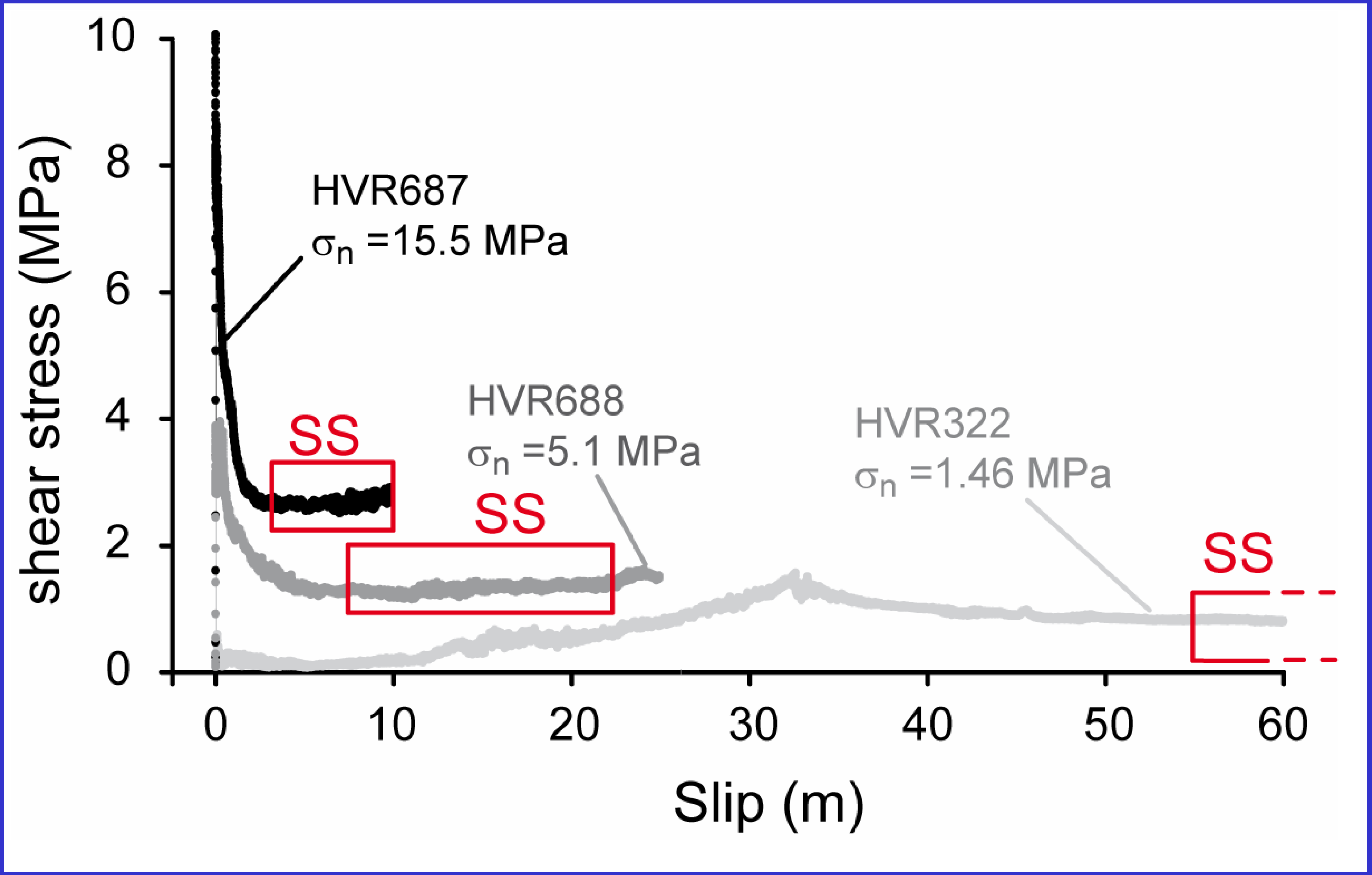
$$\tau_{ss} = \Theta^{3/4}\,\sigma_n^{1/4}\sqrt{\frac{\kappa}{R\,V}}$$

Θ	normalizing factor with stress units
κ	thermal diffusivity
R	melt escaping distance
V	slip rate

It should work for lubrication in rock, ice, etc.

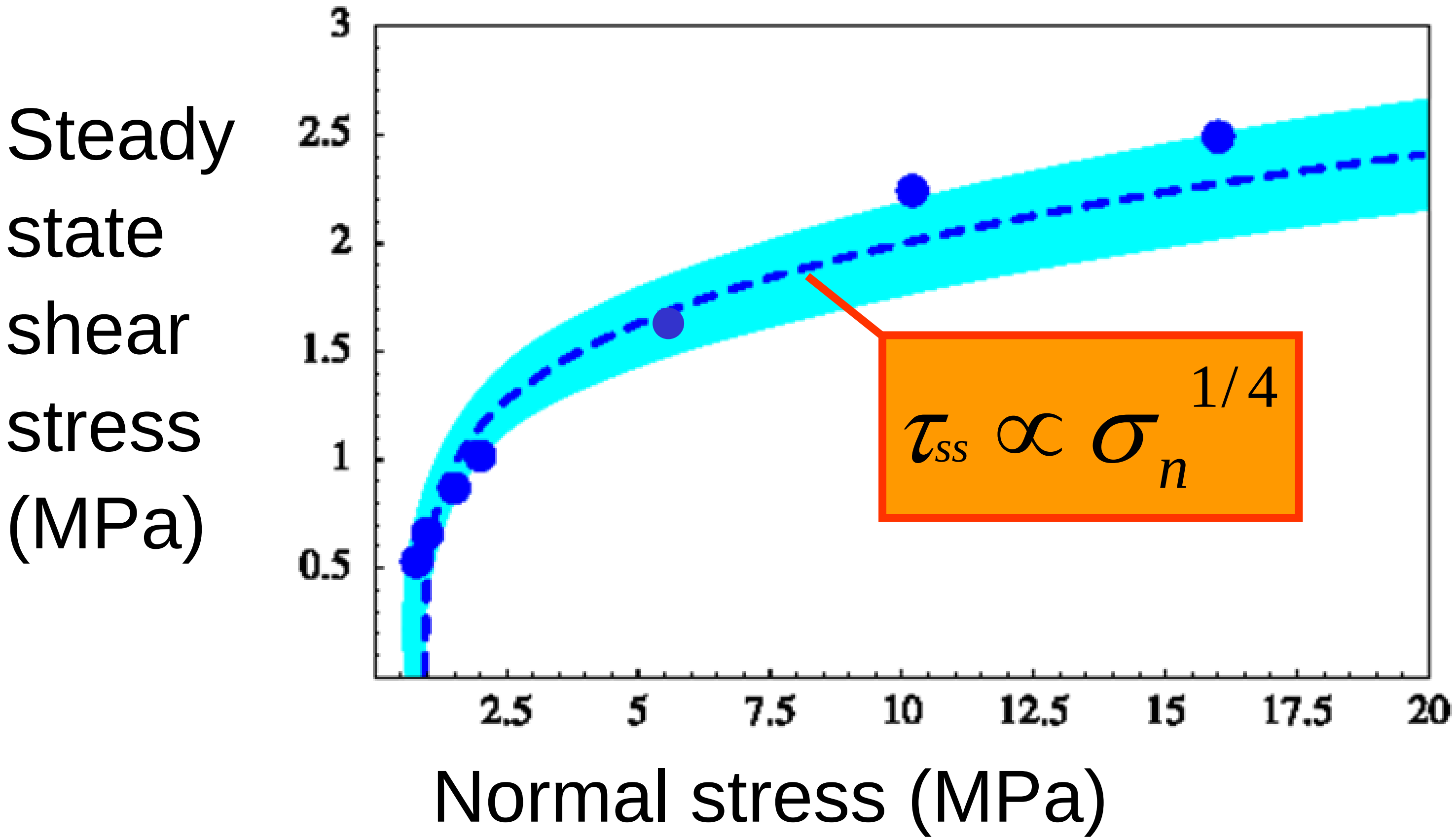
We performed experiments to test the equation (Nielsen et al., JGR, accept.)

By varying the normal stress….

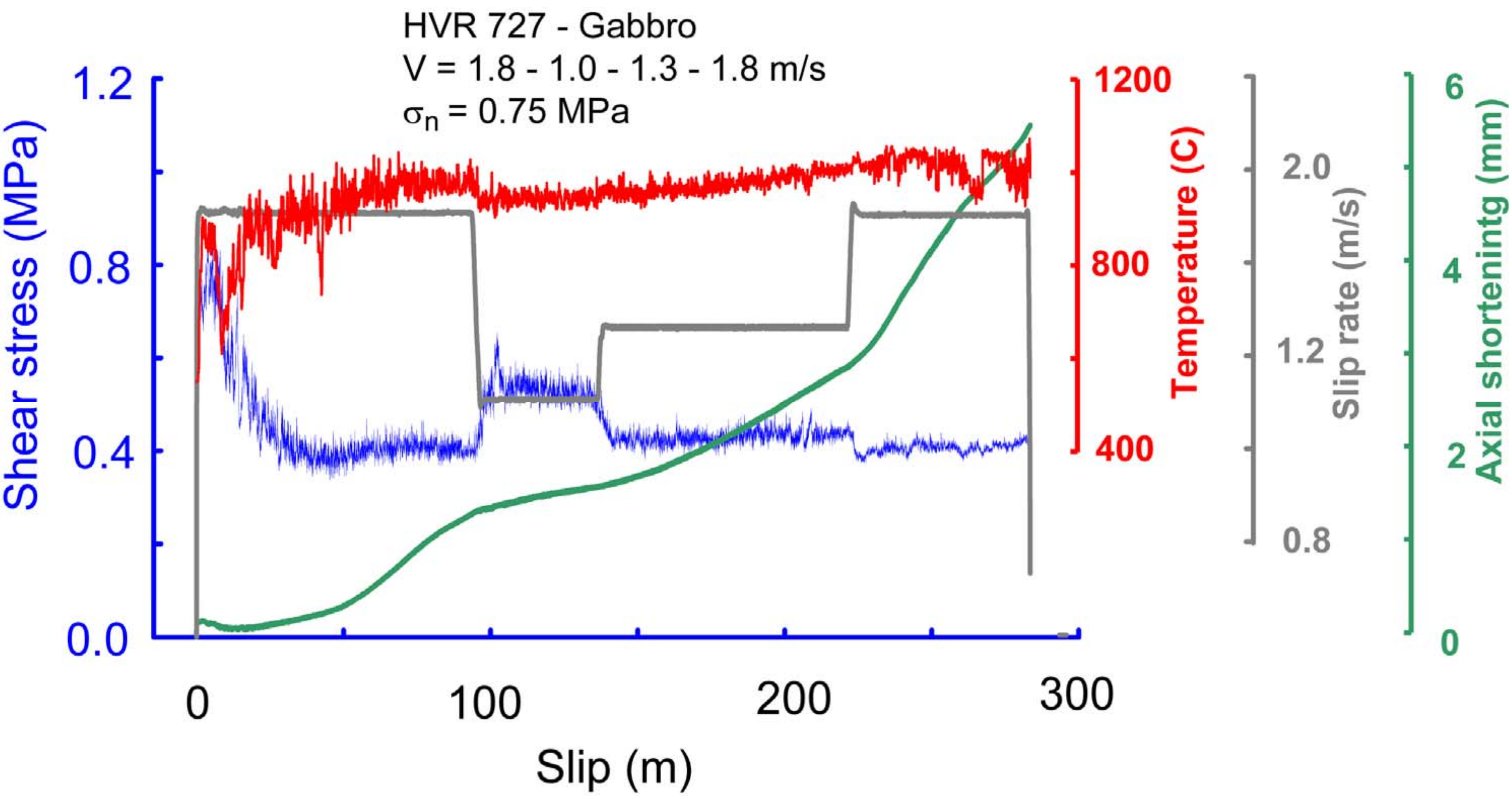


…the solution fits the shear stress dependence with normal stress.

$$\tau_{ss} = \Theta^{3/4}\,\sigma_n^{1/4}\sqrt{\frac{\kappa}{R\,V}}$$

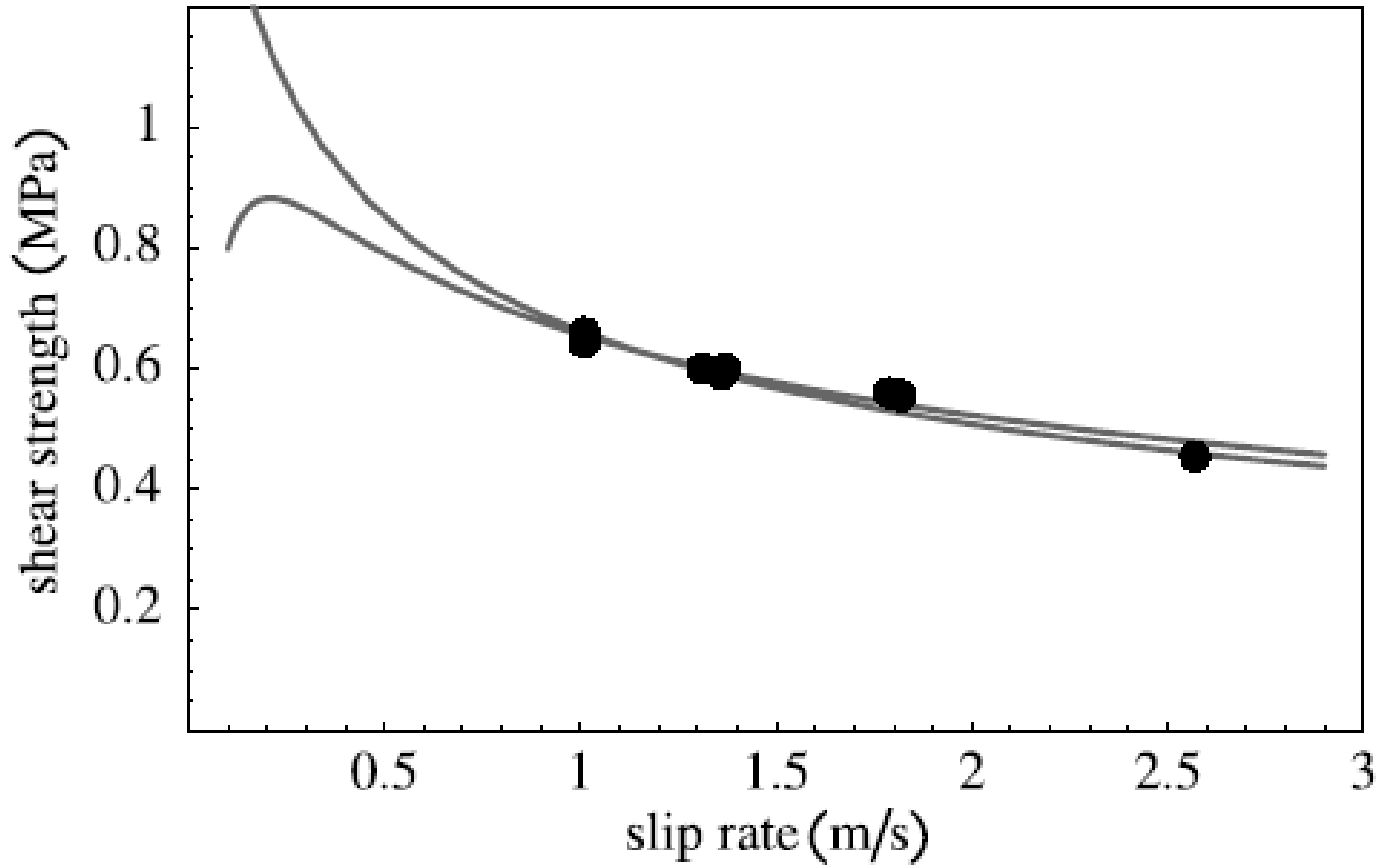


By varying the slip rate V….



..the solution fits the shear stress dependence with slip rate.

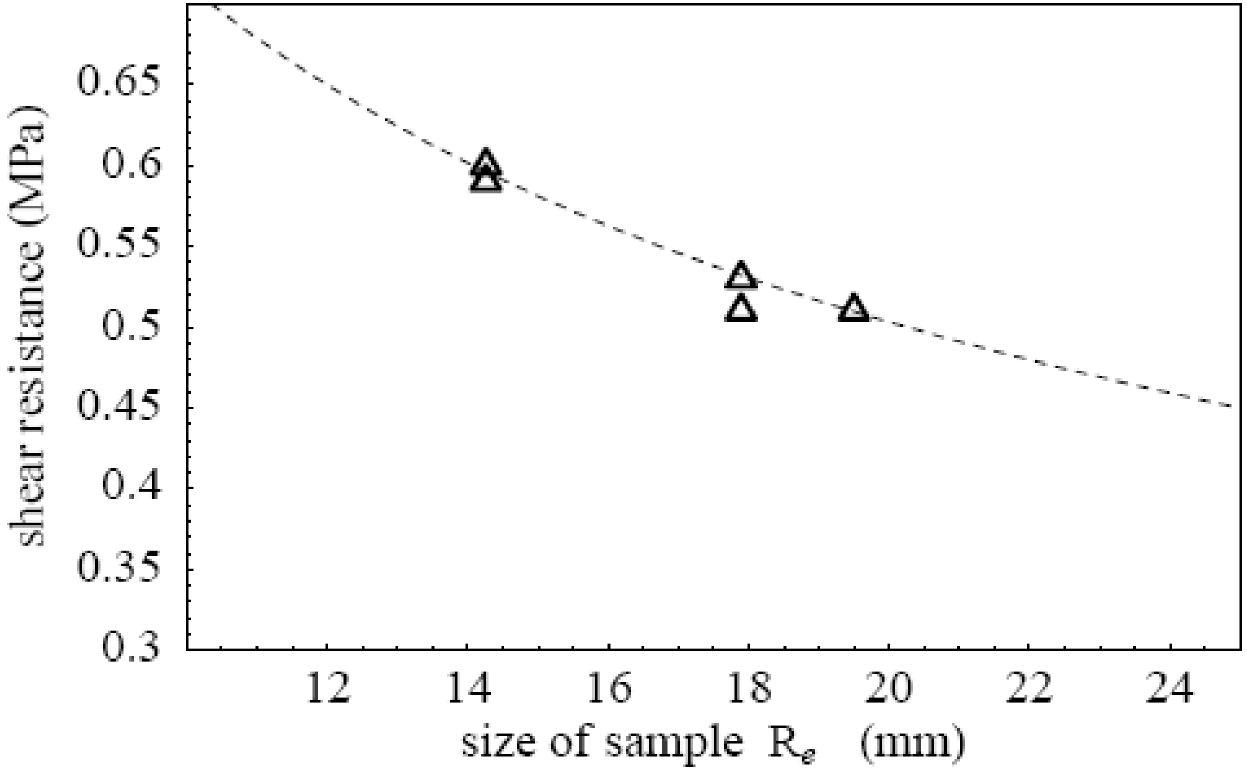
$$\tau_{ss} = \Theta^{3/4}\ \sigma_n^{1/4}\ \sqrt{\frac{\kappa}{R\,V}}$$



By varying the sample size (i.e., melt escaping dist.)

… the solution fits the shear stress dependence with the melt escaping distance.

$$\tau_{ss} = \Theta^{3/4}\,\sigma_n^{1/4}\,\sqrt{\frac{\kappa}{R\,V}}$$

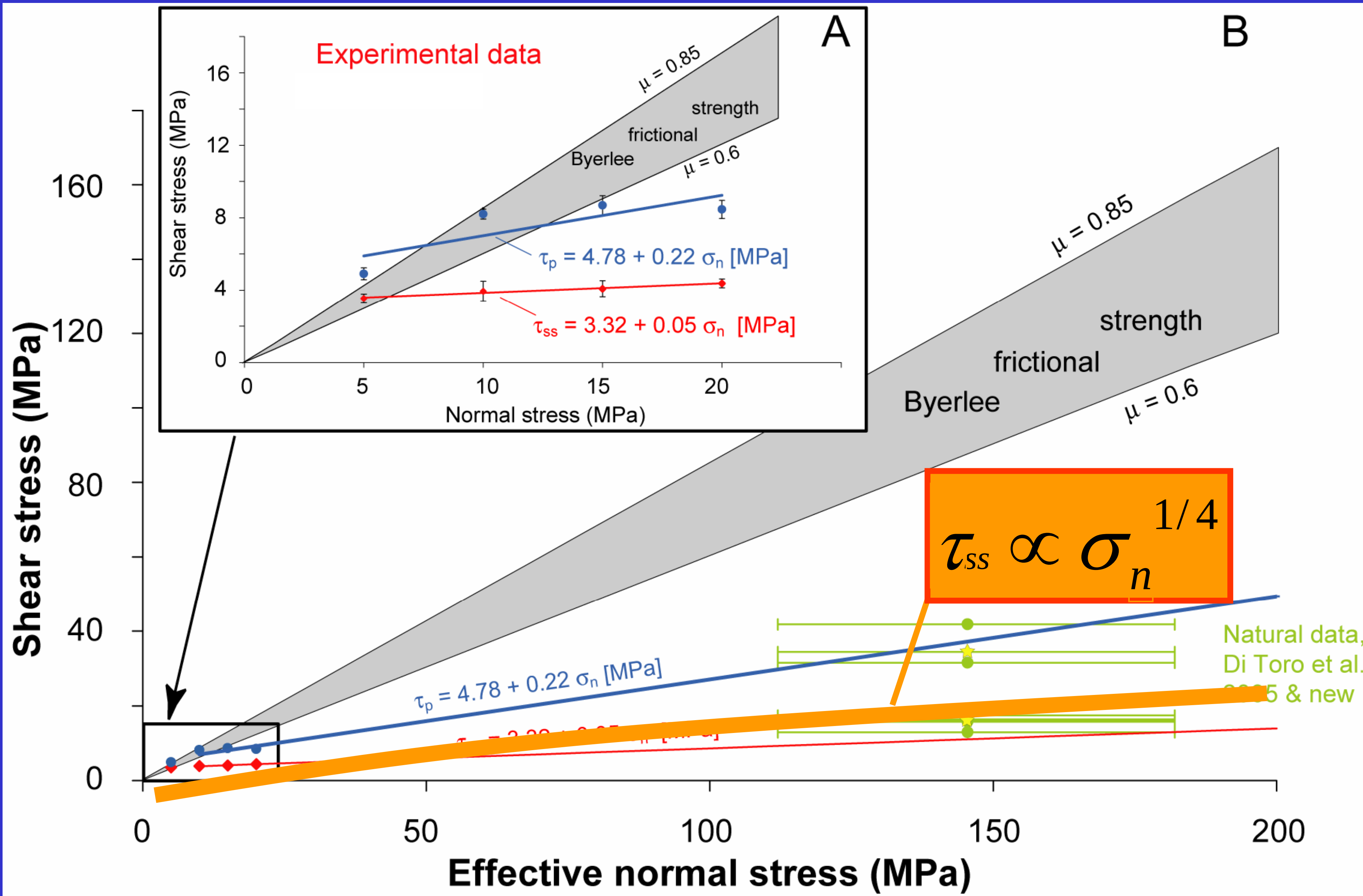


$$\tau_{ss} = \Theta^{3/4}\ \sigma_n^{1/4} \sqrt{\frac{\kappa}{R\,V}}$$

It seems that the solution for melt lubrication works.

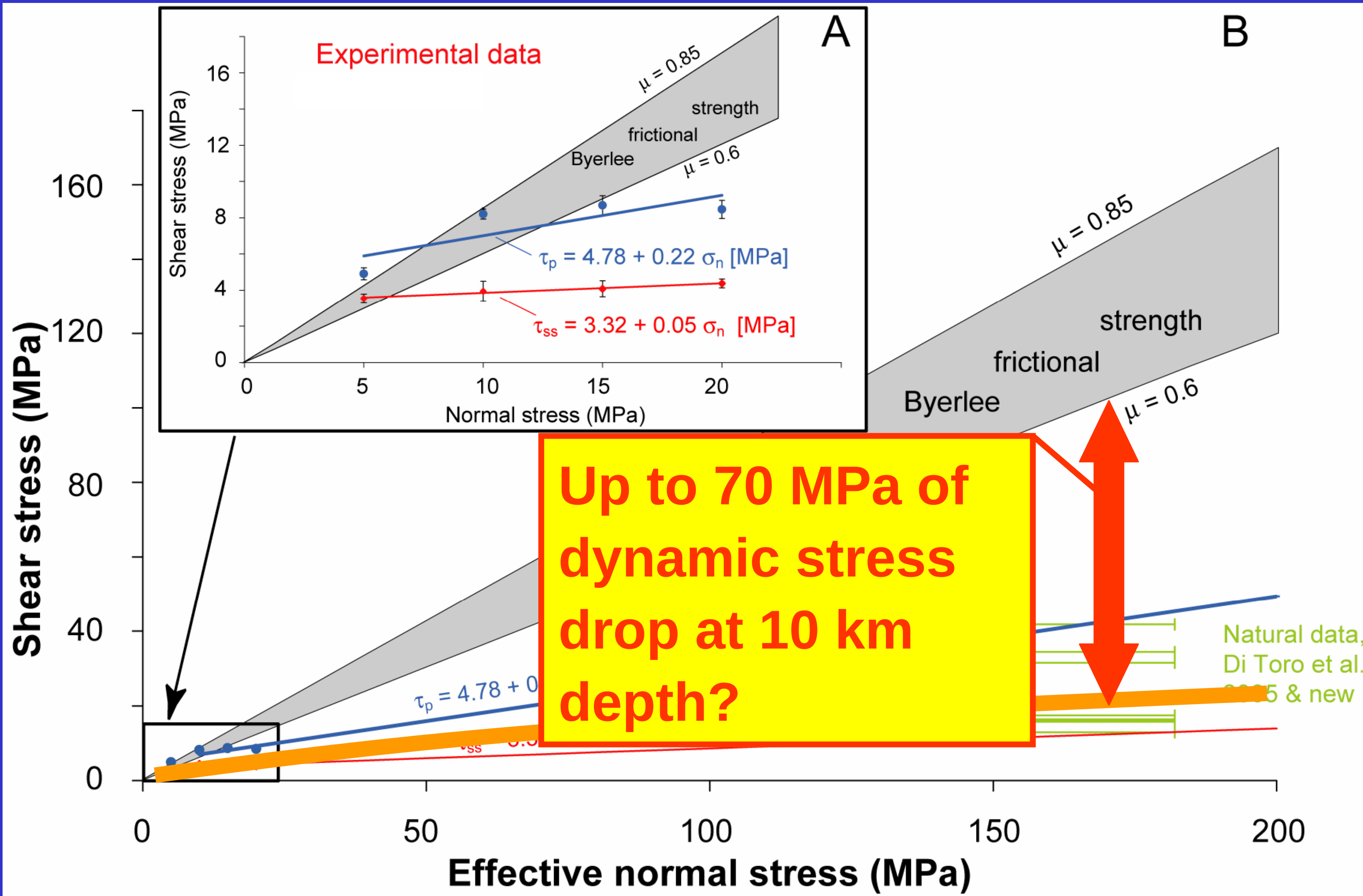
Let’s apply the Eq. to natural conditions

Melt lubrication in experiments, nature and theory



…..problems….

Large dynamic stress drops



But seismic stress drops are expected to be low (< 30 MPa) in the upper crust.

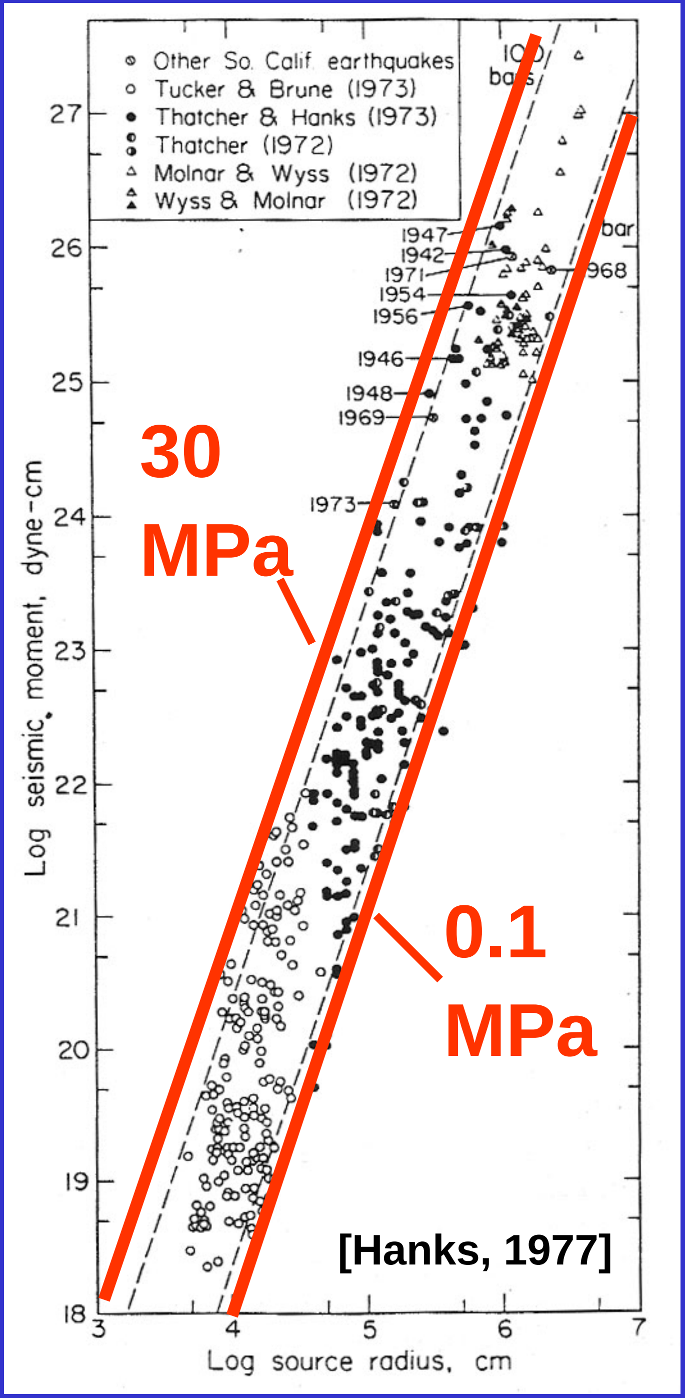
Possible answers:

~~3a) Someone is wrong.~~

3b) Dynamic stress drops 🕒 static stress drops.

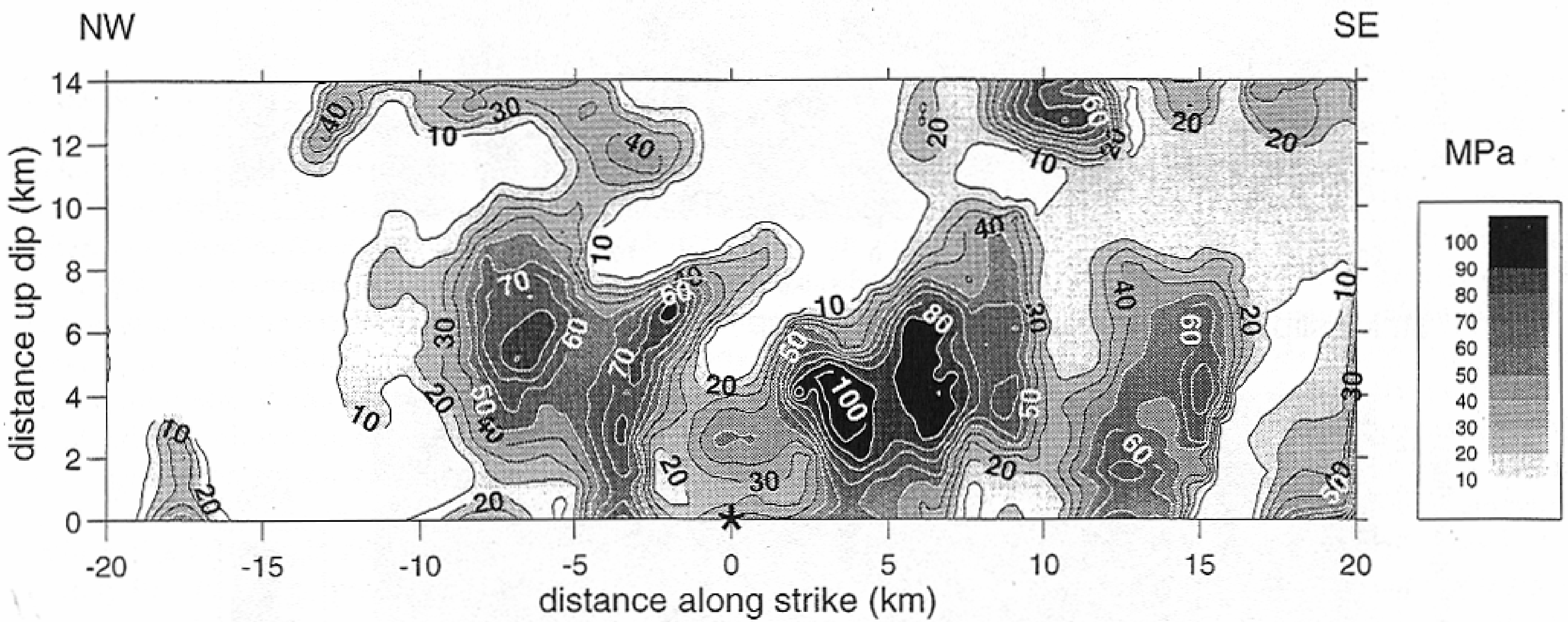
3c) Fault roughness

3d) Shear stress dependence with slip rate.



3b) Dynamic stress drops 🕒 static stress drops.

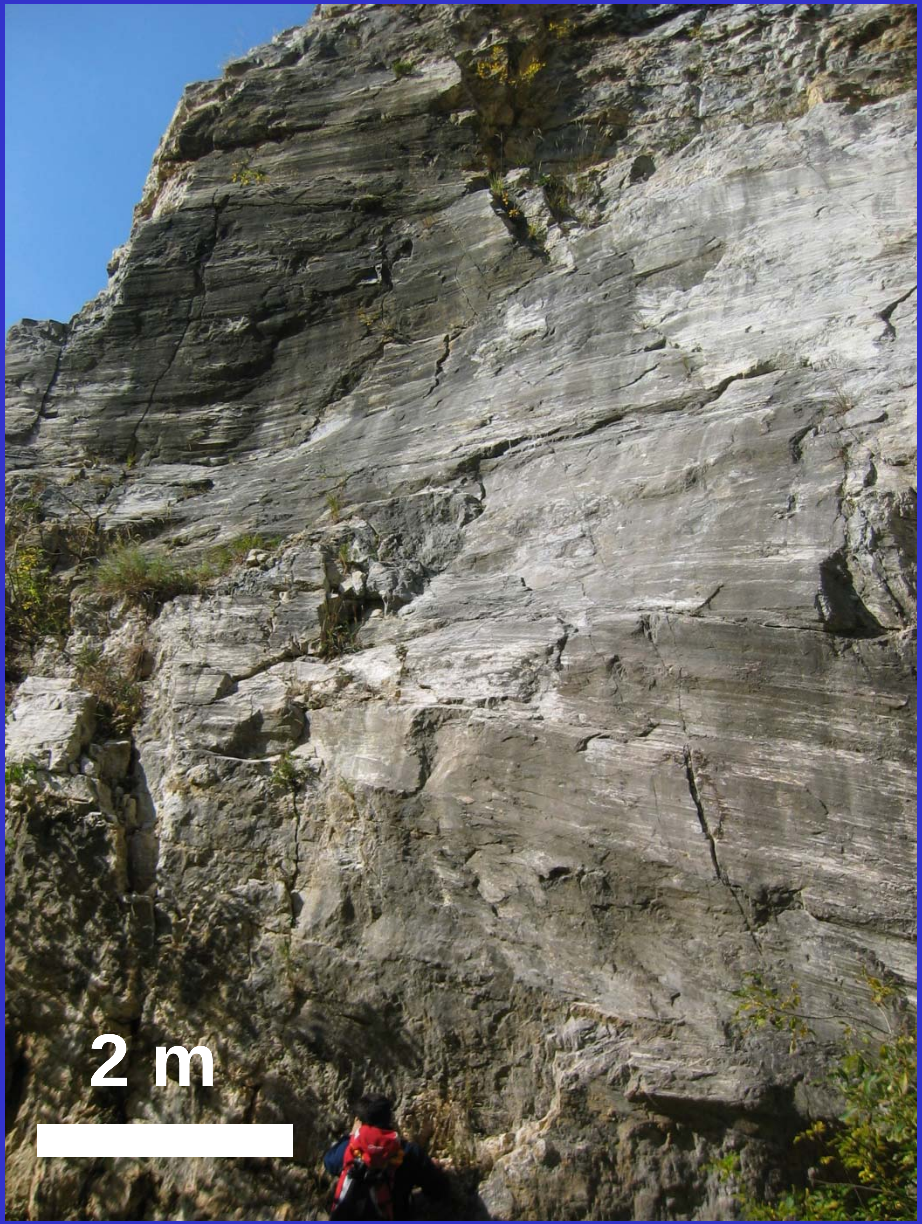
Bouchon (1997) estimated local dynamic stress drop as large as 100 MPa during the Loma Prieta (SAF) earthquake 1989, M_L = 6.9



dynamic stress drop

[Bouchon, JGR, 1997]

3c) Fault roughness

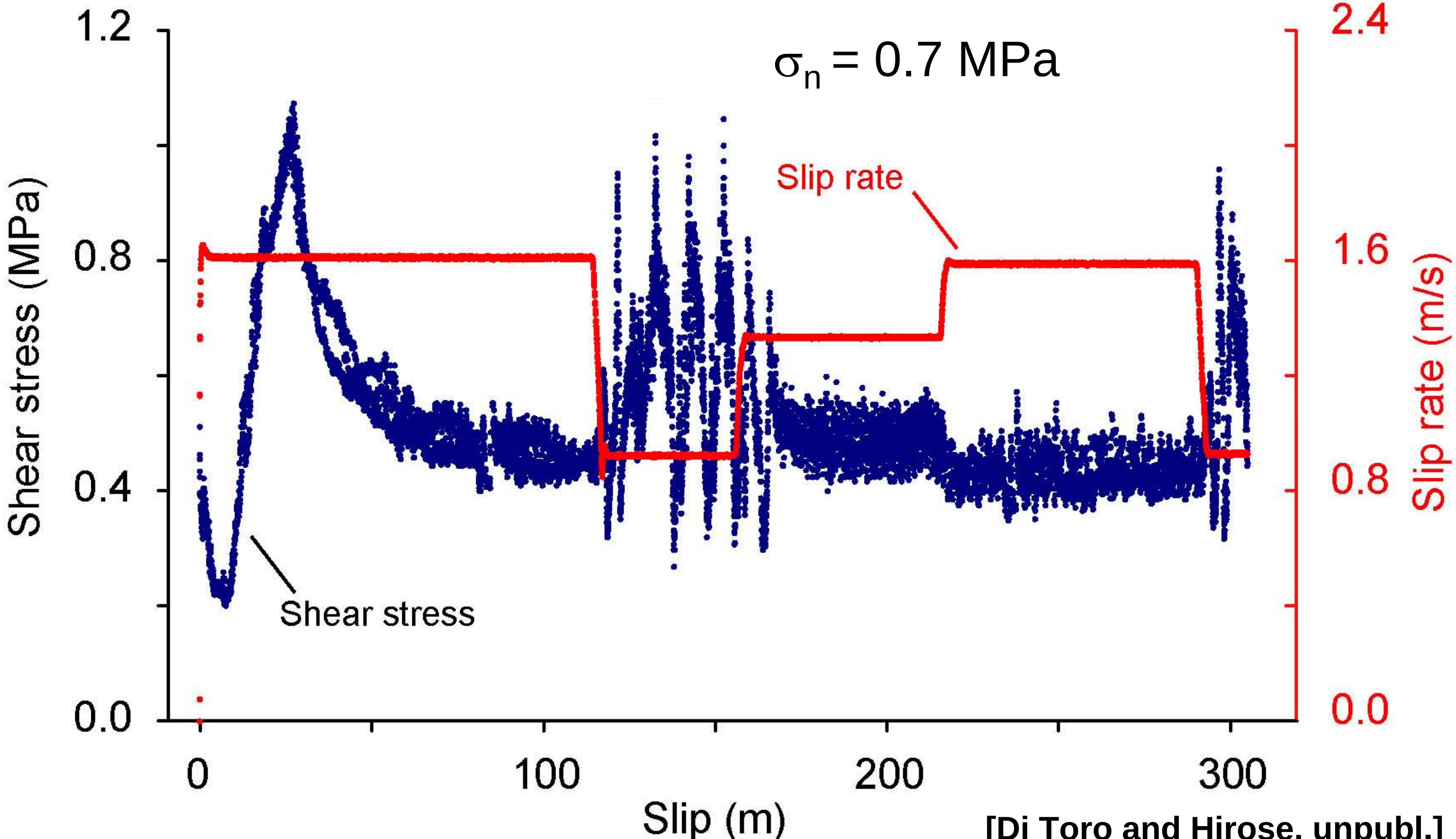


Natural faults are not as smooth as experimental sliding surfaces.

Bumps impede the smooth sliding typical of HVRFE

3d) Shear stress dependence for critical *v*

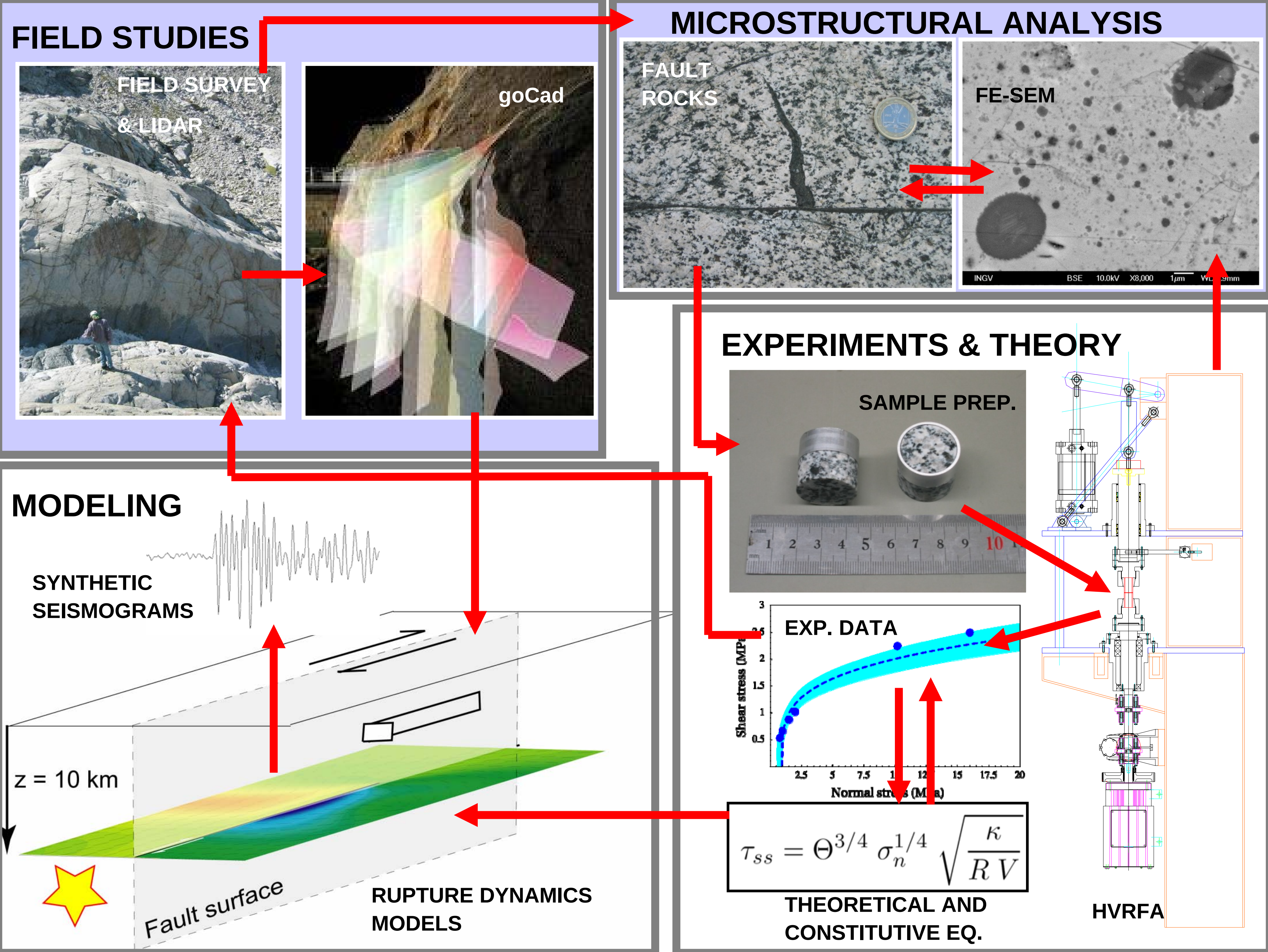
Example for melt lubrication (gabbro)



[Di Toro and Hirose, unpubl.]

To extrapolate experimental results to natural conditions,

maybe we should link….



FIELD STUDIES
FIELD SURVEY
& LIDAR
goCad
MICROSTRUCTURAL ANALYSIS
FAULT
ROCKS
FE-SEM
EXPERIMENTS & THEORY
SAMPLE PREP.
EXP. DATA
Shear stress (MPa)
Normal stress (MPa)
$\tau_{ss} = \Theta^{3/4}\,\sigma_n^{1/4}\sqrt{\frac{\kappa}{R\,V}}$
THEORETICAL AND
CONSTITUTIVE EQ.
HVRFA
MODELING
SYNTHETIC
SEISMOGRAMS
z = 10 km
Fault surface
RUPTURE DYNAMICS
MODELS

Conclusions

1) Rocks have low μ at seismic slip rates.

2) In some cases, experimental fault products are identical to natural ones.

3) HVRFE allow the determination of new rock friction constitutive equations.

4) Extrapolation of experimentally-derived results to dynamic rupture models is not trivial.

“Go my sons, buy stout shoes, climb the mountains, search the valleys, the deserts, the sea shores, and the deep recess of the earth. Look for the various kinds of minerals, note their characters and mark their origin.

Lastly, buy coal, build furnaces, observe and experiment without ceasing, for in this way and in no other will you arrive at knowledge of the nature and properties of things”.

Marco Aurelio Severino, naturalist (1580-1656)

Main experimental results for *v* < 10 mm/s and *d* < 1 cm

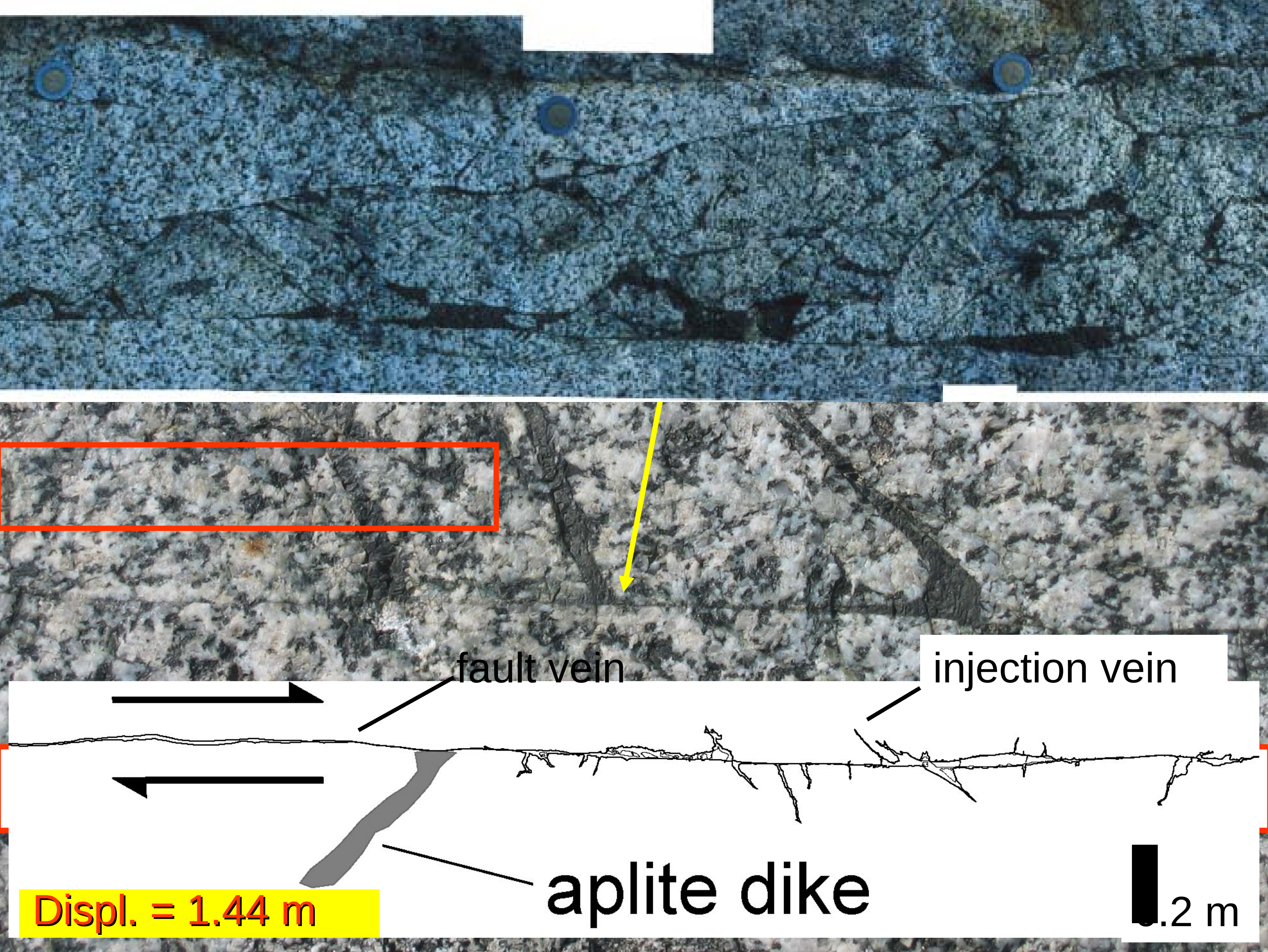
- μ is 0.60 - 0.85 [*Byerlee*, 1978]

- μ varies of few % for small changes in slip rate

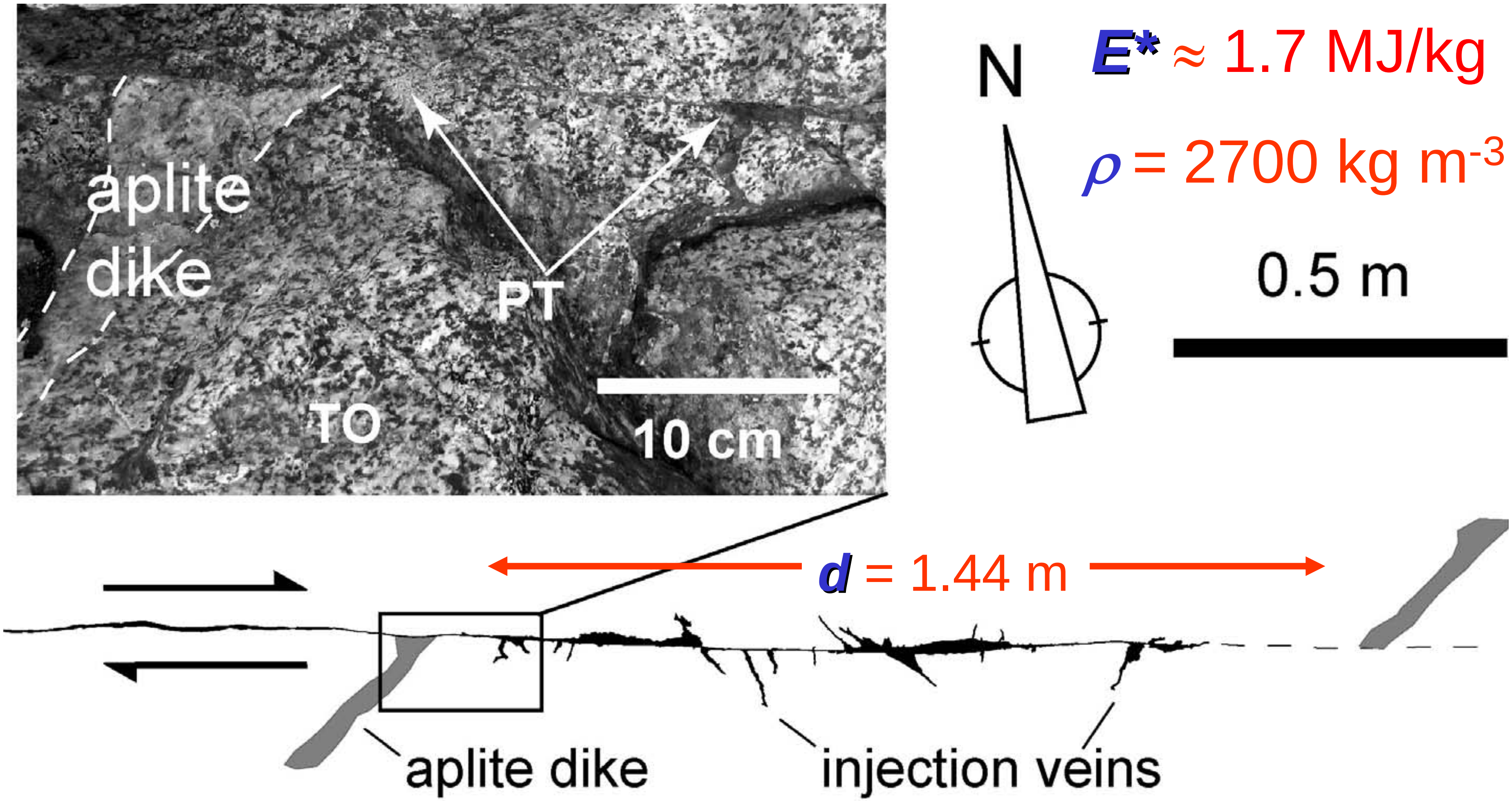
- μ is a function of sliding speed: rate- and state-dependent friction law (Dieterich-Ruina law)

- Dc is tens to hundreds of microns max.


NIED 2007
Designed by Mizoguchi & Shimamoto
σ_n < 20 MPa
v = 0.1 μm/s - 10 m/s
d = infinite
Servo Control Unit
POWER SUPPLY


fault vein
injection vein
aplite dike
Displ. = 1.44 m
.2 m

Determination of average dynamic shear stress



$E^* \approx 1.7$ MJ/kg

$\rho = 2700$ kg m^{-3}

$d = 1.44$ m

t = area (PT) / fault length segment = 5.9 mm

$$\tau_{av} \approx (t / d)\, E^* \rho = 18.4 \quad \text{MPa}$$

Estimate of τ_{av} from PT-bearing faults:

$$\tau_{av} \approx (t\ /\ d)\ E^*\ \rho \qquad \text{in Pa}$$

[mod. from *Sibson*, 1975]

τ_{av}	average dynamic shear stress in Pa
t	average pseudotachylyte thickness in m
d	coseismic fault displacement in m
E^*	energy to heat and melt 1 kg of rock (1.7 MJ kg^{-1})
ρ	rock density 2700 kg m^{-3}

Main assumption:

All work done in faulting is converted to heat –fracture surface energy is negligible [Pittarello et al., S33-xxx]

Energy E to heat and melt a volume of rock

$$\boxed{E = E_{melt} + E_{heat}}$$

$$E = [c_{pm}\,(T)\,\Delta T + H\,]\,v_m / v_{pt} + [c_{pcl}\,(T)\,\Delta T\,]\,(v_{pt} - v_m)/ v_{pt}$$

H	latent heat of fusion (J kg^{-1})
$\Delta T = T_{melt} - T_{hr}$	temperature difference between host rock and PT (K)
c_{pm}	specific heat for friction-induced melt (kJ K^{-1} mol^{-1})
c_{pcl}	specific heat for clasts (kJ K^{-1} mol^{-1})
v_m / v_{pt}	matrix content
$(v_{pt} - v_m) / v_{pt}$	clast content

if: $c_{pm}\,(T) \approx c_{pcl}\,(T)$

$$\boxed{E = [(v_m / v_{pt})\,H + c_p\,(T)\,\Delta T\,] \quad \text{in J/kg}}$$

Melted rock mass
$M = \rho A t$

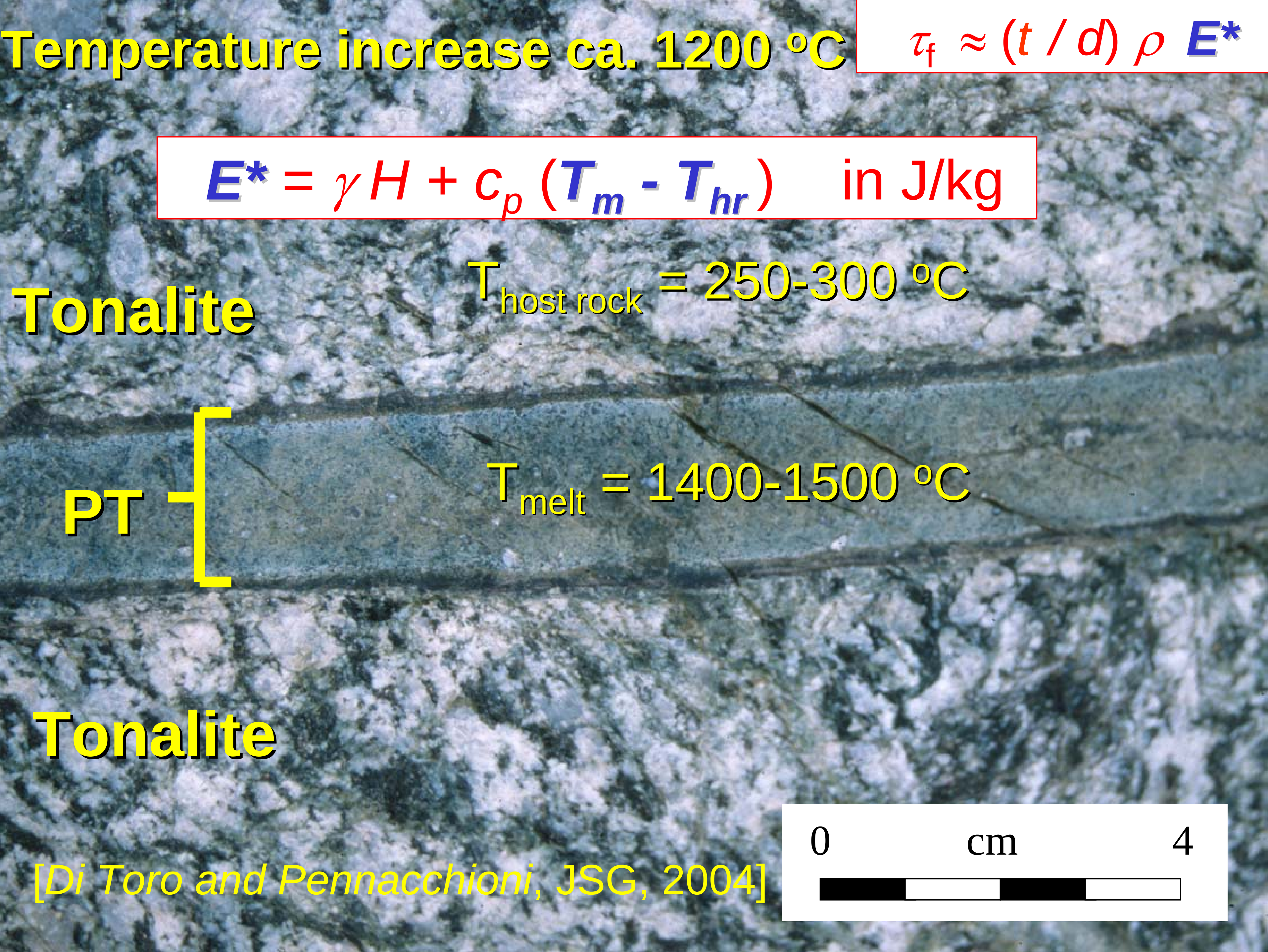
$$\boxed{Q = E\,M = [(v_m / v_{pt})\,H + c_p\,(T)\,\Delta T\,]\,\rho A t \quad \text{in J}}$$

$W_f = \tau\, d\, A = Q$

$$\boxed{\tau\;\; d\, A = [(v_m / v_{pt})\,H + c_p\,(T)\,\Delta T\,]\,\rho A t}$$

t = thickness
d =displacement

$$\boxed{\tau = \rho\;E\;\;(t\,/\,d) \quad \text{in Pa}}$$

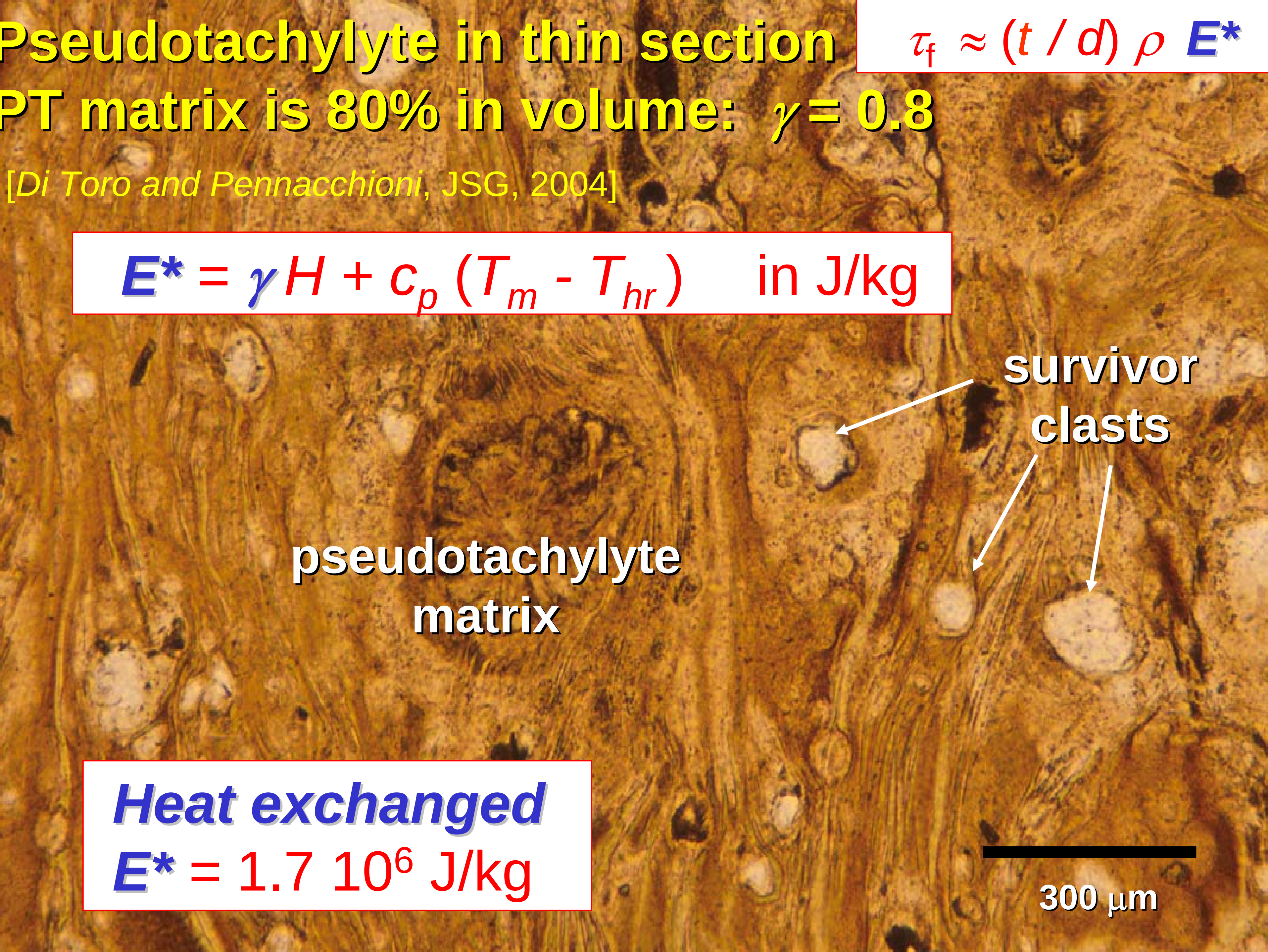

Temperature increase ca. 1200 °C
$\tau_f \approx (t / d)\, \rho\, E^*$
$E^* = \gamma H + c_p (T_m - T_{hr})$ in J/kg
Tonalite
$T_{host\ rock}$ = 250-300 °C
PT
T_{melt} = 1400-1500 °C
Tonalite
[Di Toro and Pennacchioni, JSG, 2004]
0 cm 4

Pseudotachylyte in thin section
PT matrix is 80% in volume: $\gamma = 0.8$

[*Di Toro and Pennacchioni*, JSG, 2004]

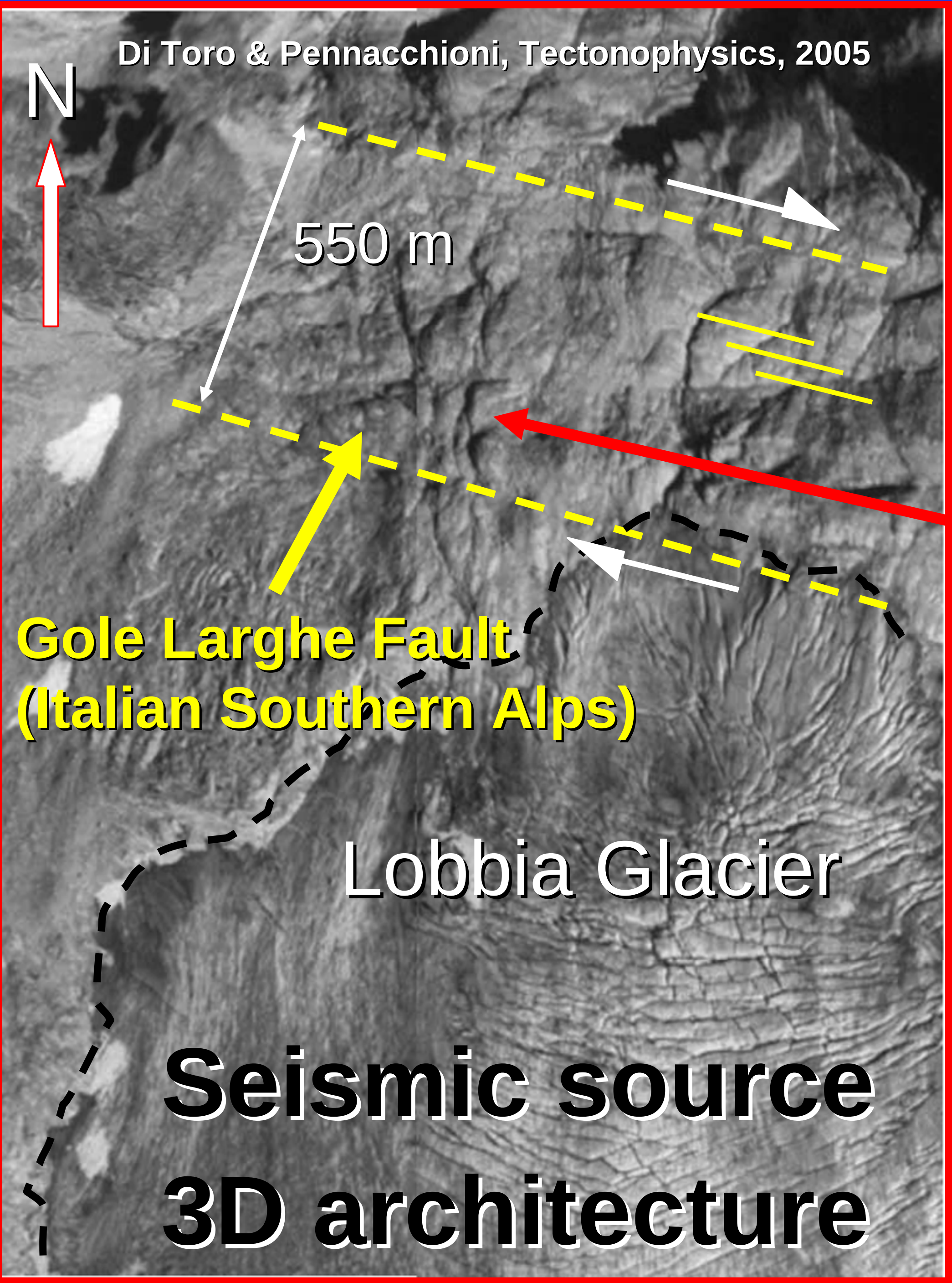
$\tau_f \approx (t / d)\, \rho\, E^*$

$E^* = \gamma H + c_p\,(T_m - T_{hr})$ in J/kg



Heat exchanged

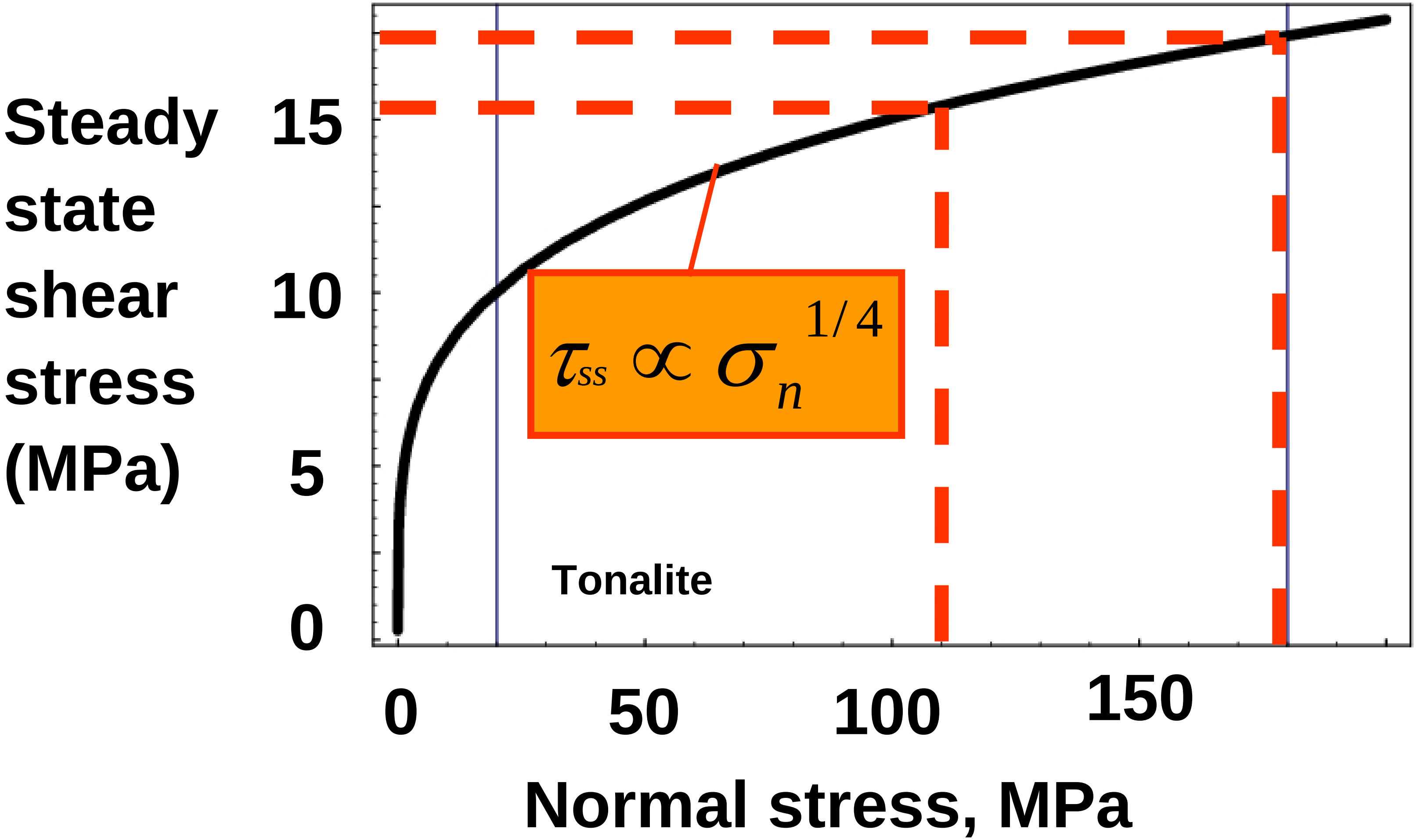
$E^* = 1.7\ 10^6$ J/kg


Di Toro & Pennacchioni, Tectonophysics, 2005
N
550 m
Gole Larghe Fault
(Italian Southern Alps)
Lobbia Glacier
Seismic source
3D architecture

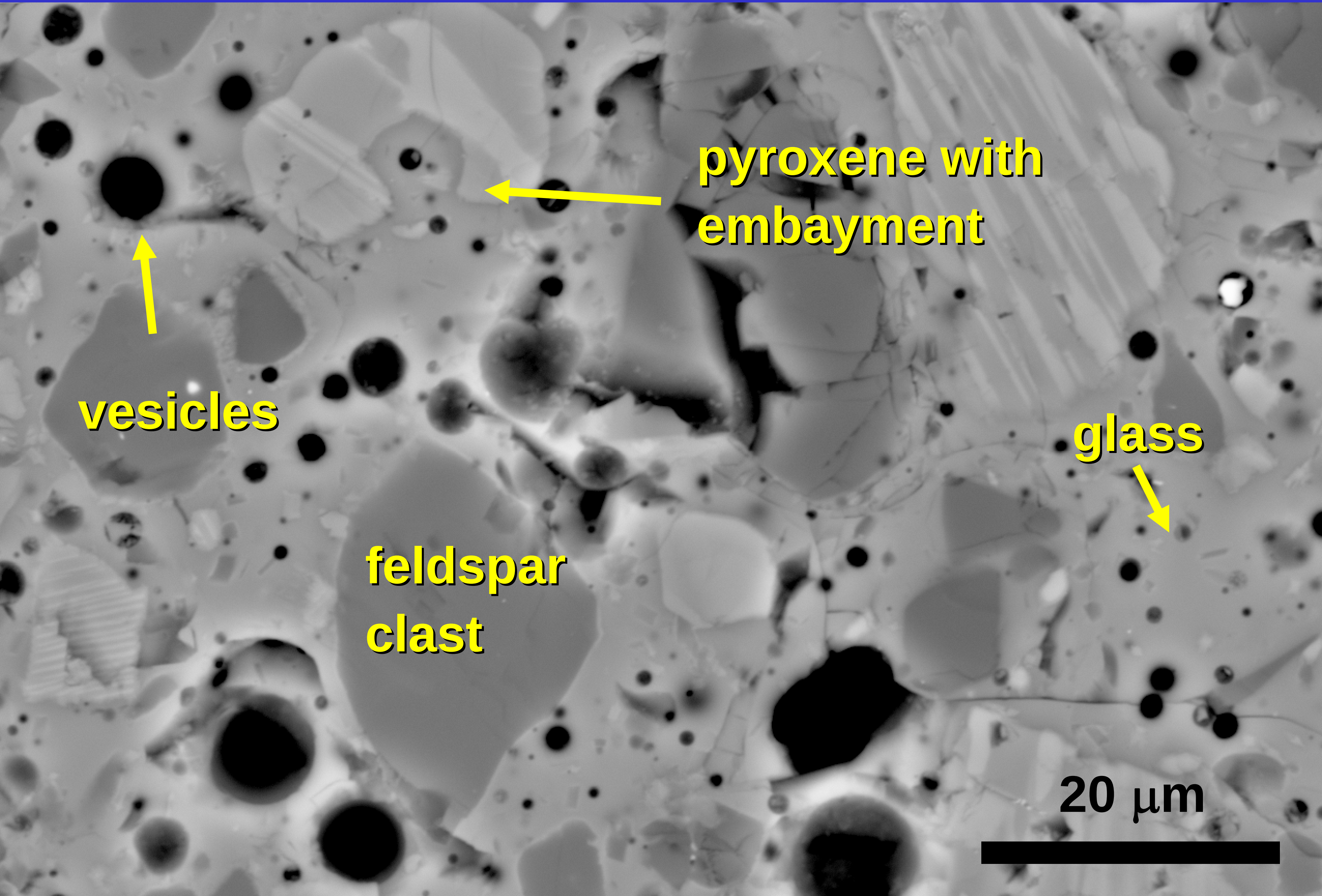
Estimate for τ_{ss} at 10km depth ~ 16 MPa

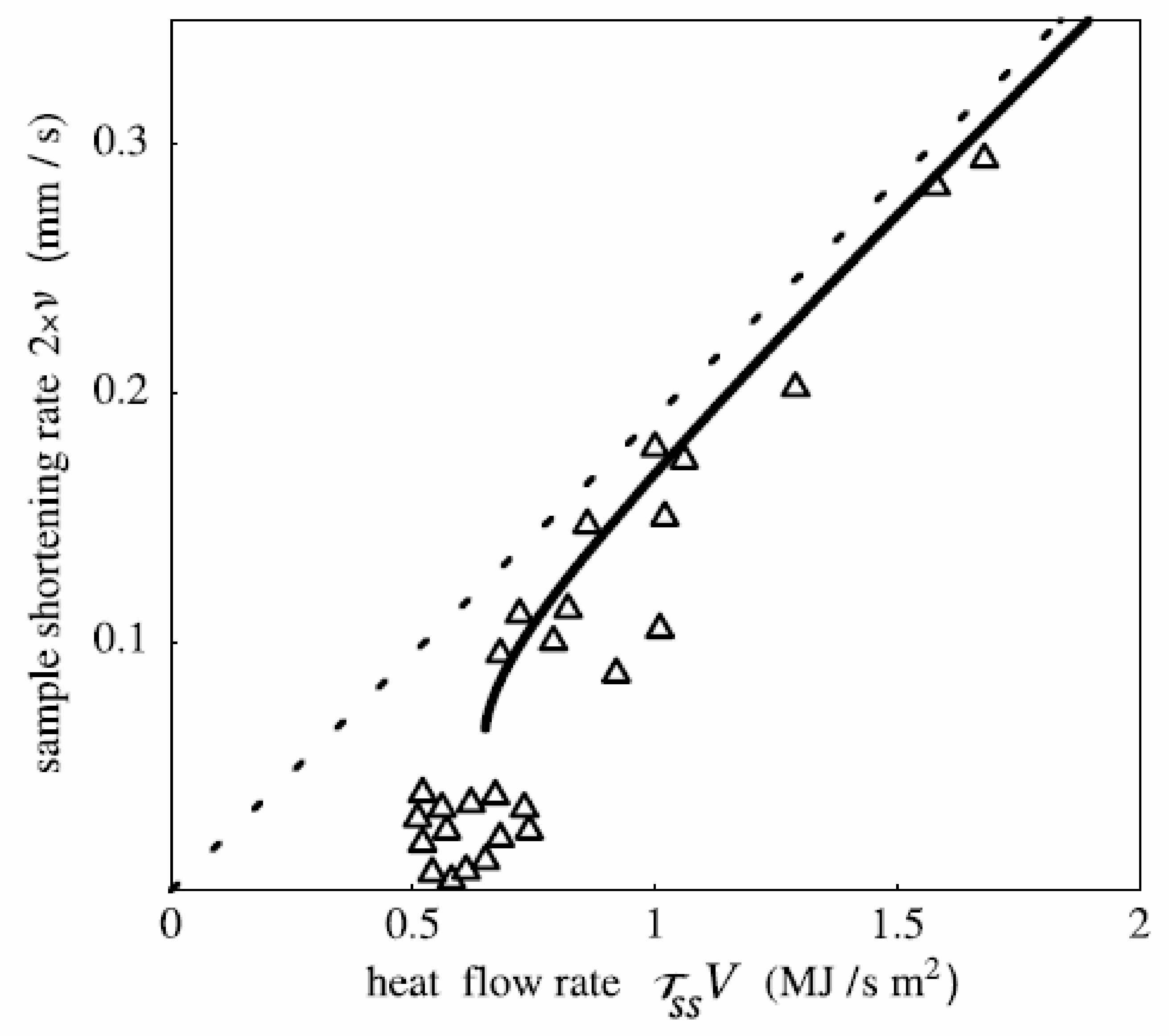
τ_{ss} ~ 15-17.5 MPa

For σ_n ~150 MPa and V = 1 m/s

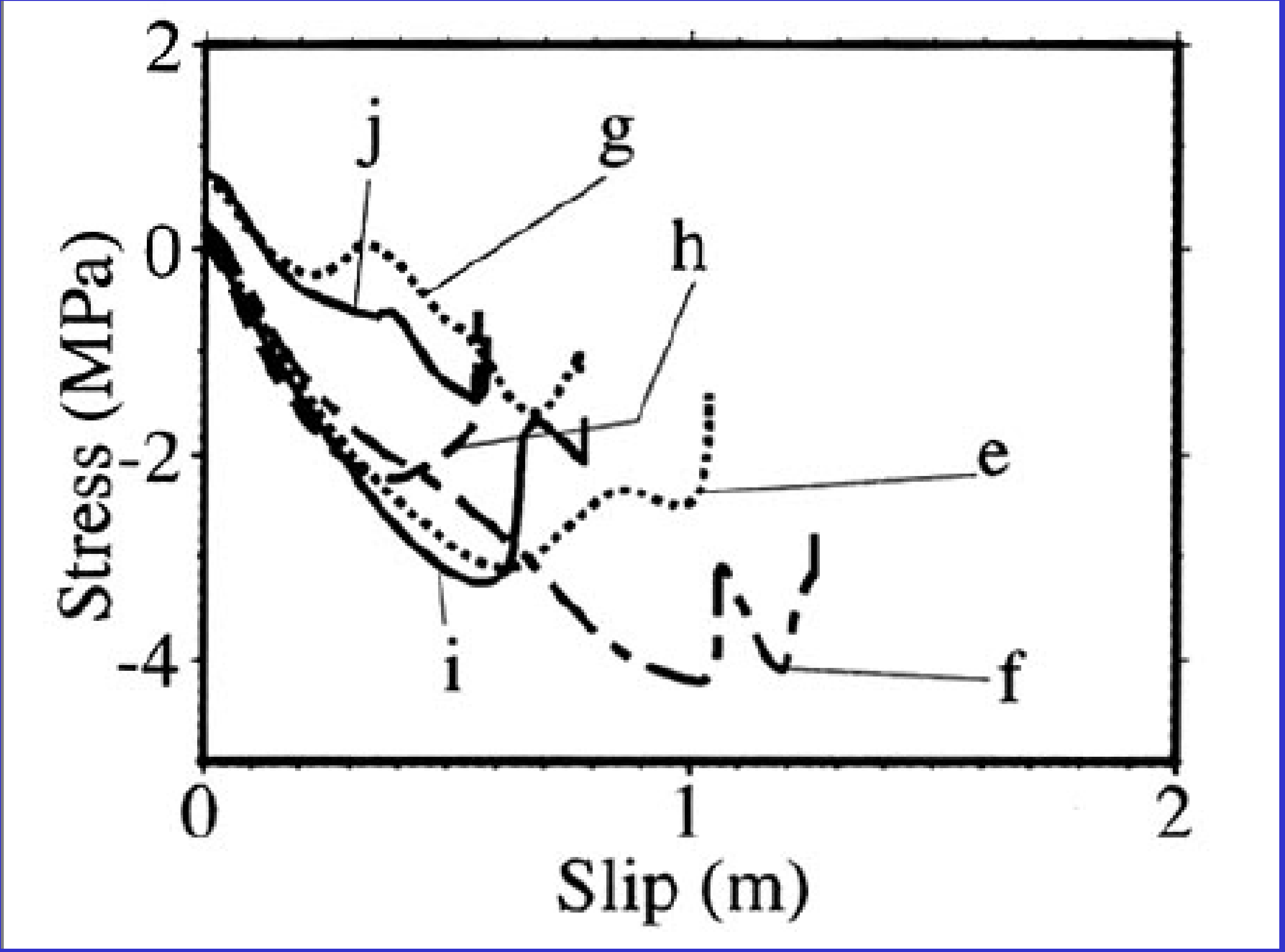


SEM image of the slipping zone after the exp.





sample shortening rate $2\times v$ (mm / s)
0.1
0.2
0.3
0
0.5
1
1.5
2
heat flow rate $\tau_{ss}V$ (MJ / s m^2)



2
0
-2
-4
0
1
2
Stress (MPa)
Slip (m)
j
g
h
e
f
i

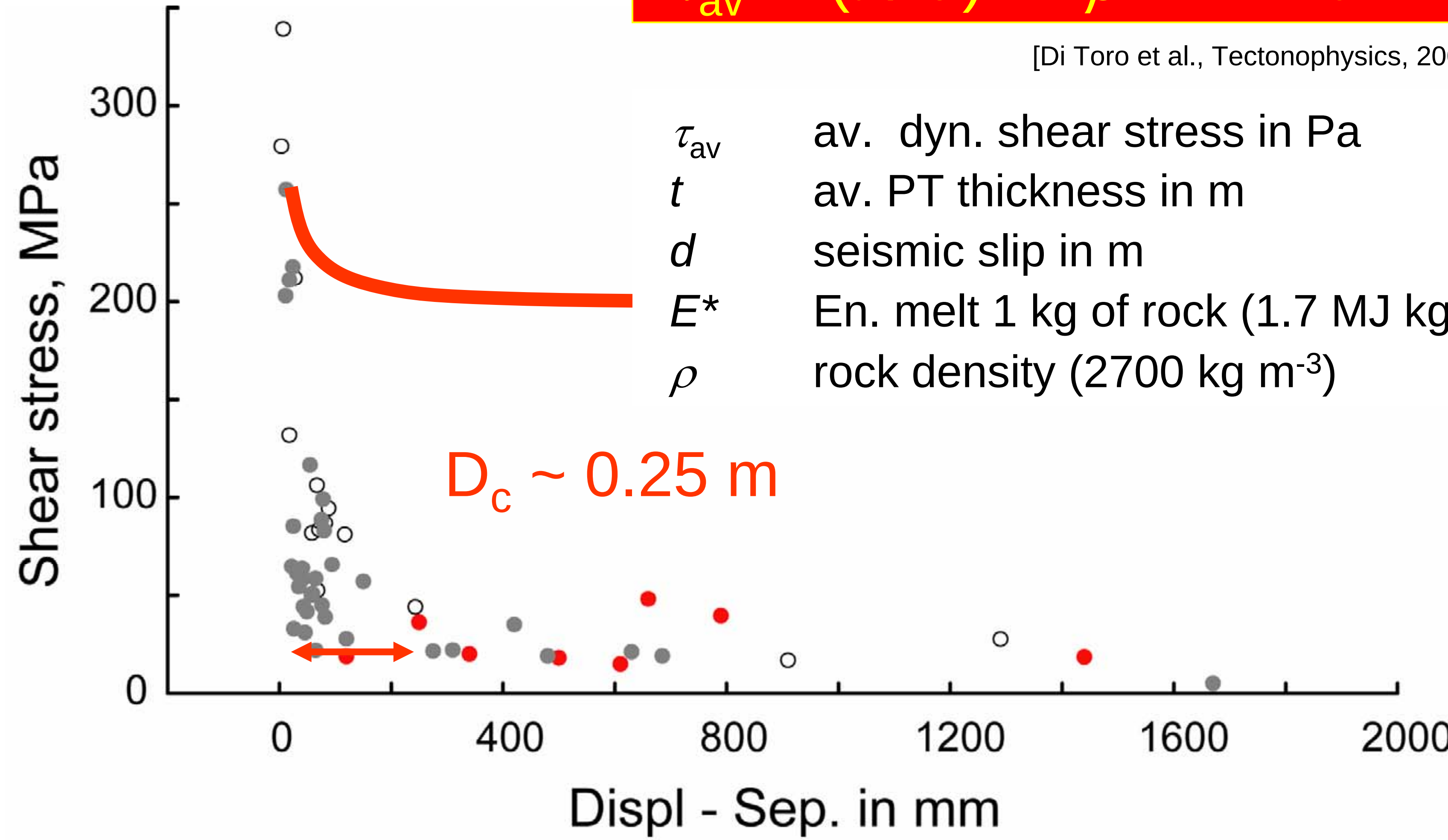
We determined displ. *d* from separations

Slip weakening distance in the presence of melt

$$\tau_{av} \approx (t / d)\, E^* \rho \quad \text{in Pa}$$

[Di Toro et al., Tectonophysics, 2005]

τ_{av}	av. dyn. shear stress in Pa
t	av. PT thickness in m
d	seismic slip in m
E^*	En. melt 1 kg of rock (1.7 MJ kg^{-1})
ρ	rock density (2700 kg m^{-3})



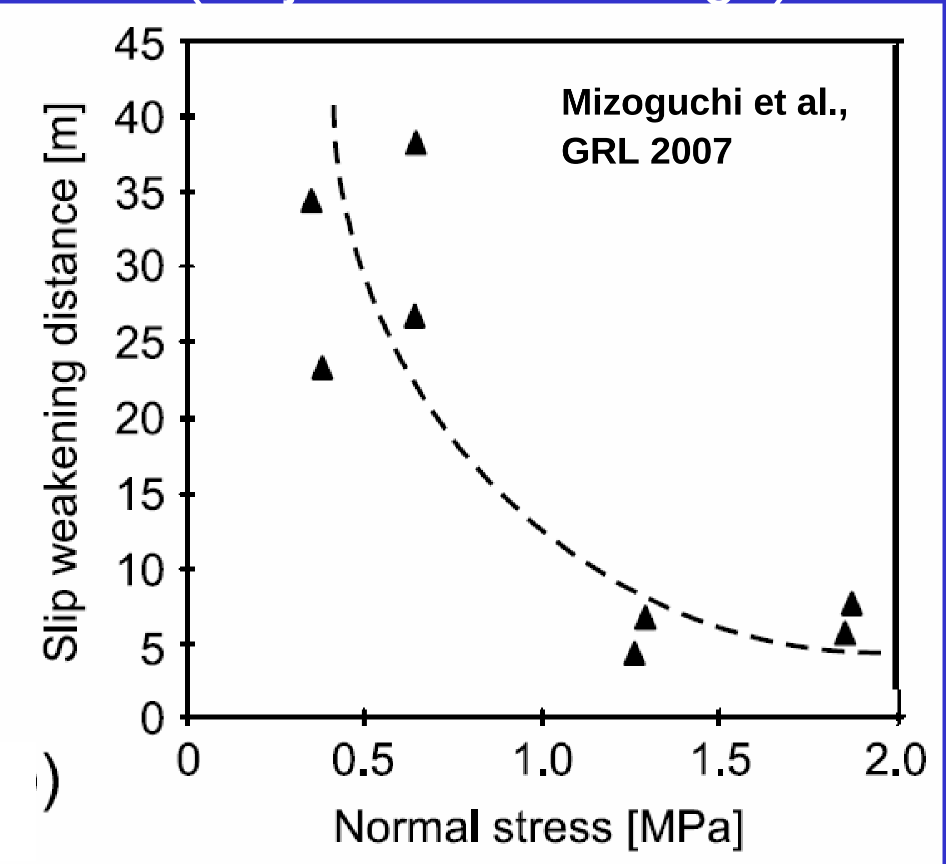
D_c of 0.25 m is consistent with estimates from independent theoretical analyses (see also Di Toro et al., S33A-0220 and Nielsen et al., S33B-0238)

$$D_c = 8\,\kappa\,[\rho\,[H + c_p\,(T_m - T_{hr})]\,/\tau]^2 /\,V$$

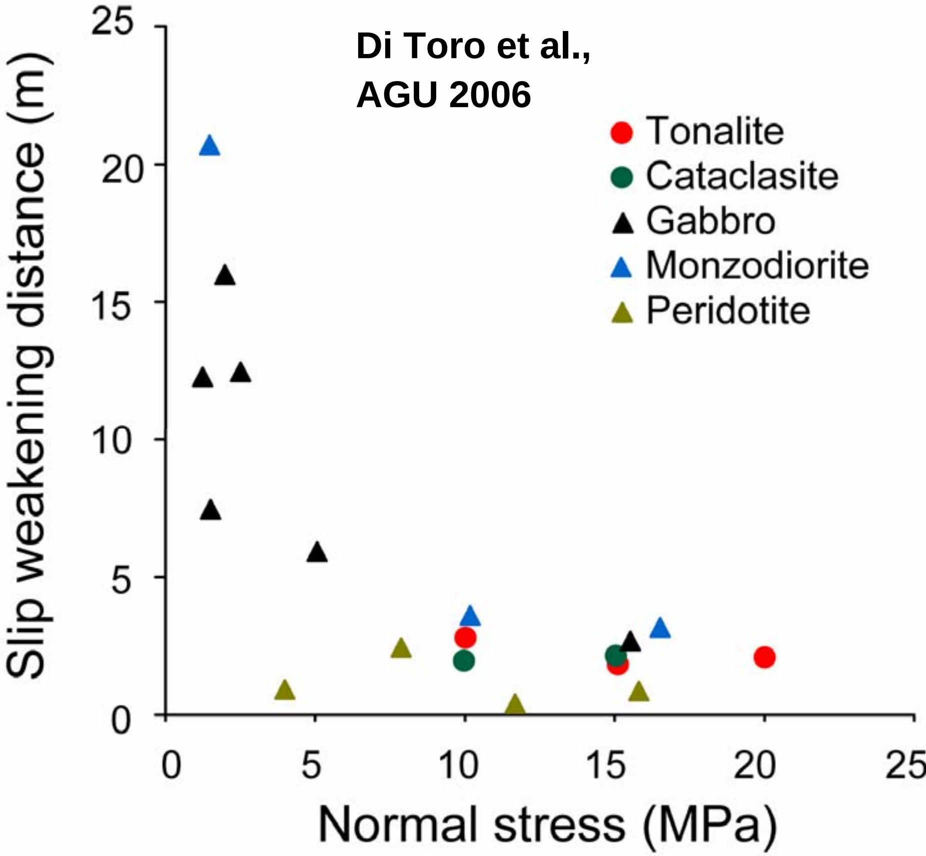
κ	thermal diffusivity ($1.8\ 10^{-6}$ $m^2\,s^{-1}$)
ρ	rock density (2700 kg m^{-3})
H	latent heat of fusion ($3.3\ 10^5$ J kg^{-1})
c_p	specific heat (1180 J kg^{-1} K^{-1})
T_m	melt temp. (~ 1450 ^{o}C)
T_{hr}	host rock temp.(~250 ^{o}C)
τ	shear stress (22 MPa)
V	slip rate (1 m s^{-1})

How can we extrapolate HVRFE to nature? Dc decreases with increasing normal stress towards seismically inferred Dc (~1 m)

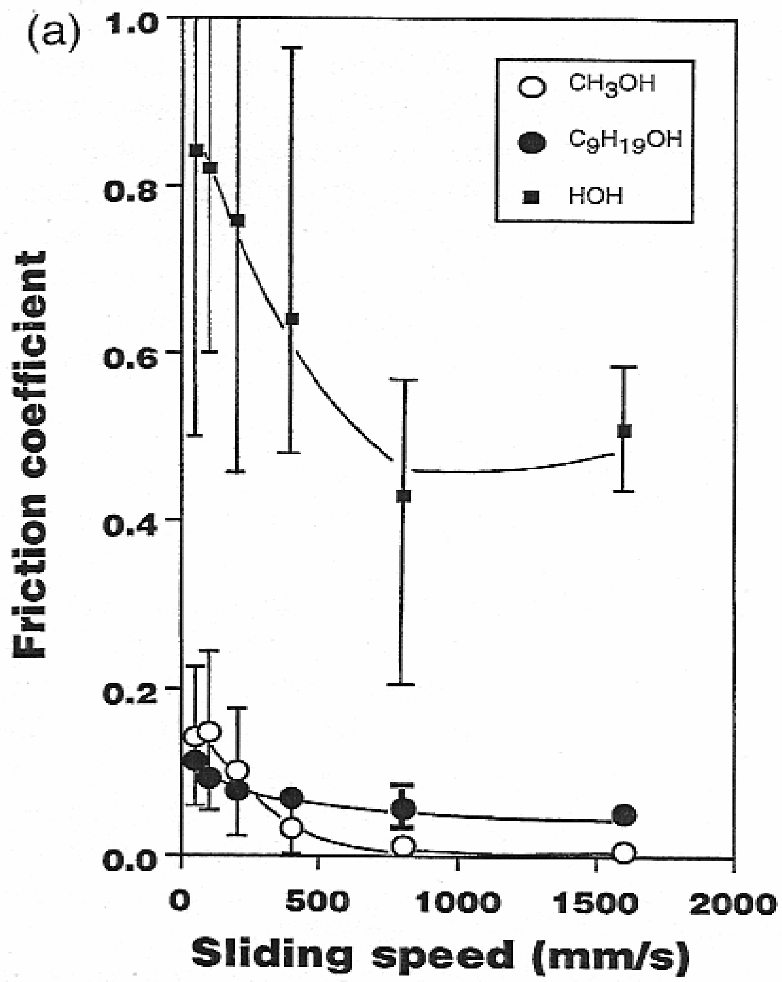
Non-cohesive rocks
(Nojima Fault Gouge)



Cohesive rocks
(frictional melting)

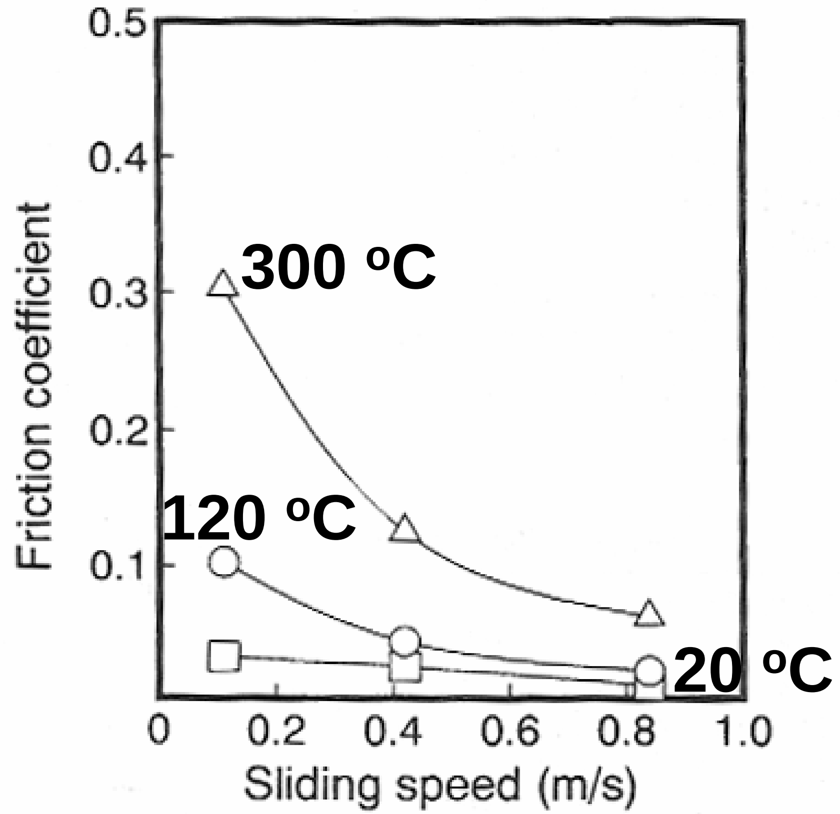


Tribochemical reactions: velocity weakening in Si-bearing compounds



Si_3N_4 in H_2O and alcohol

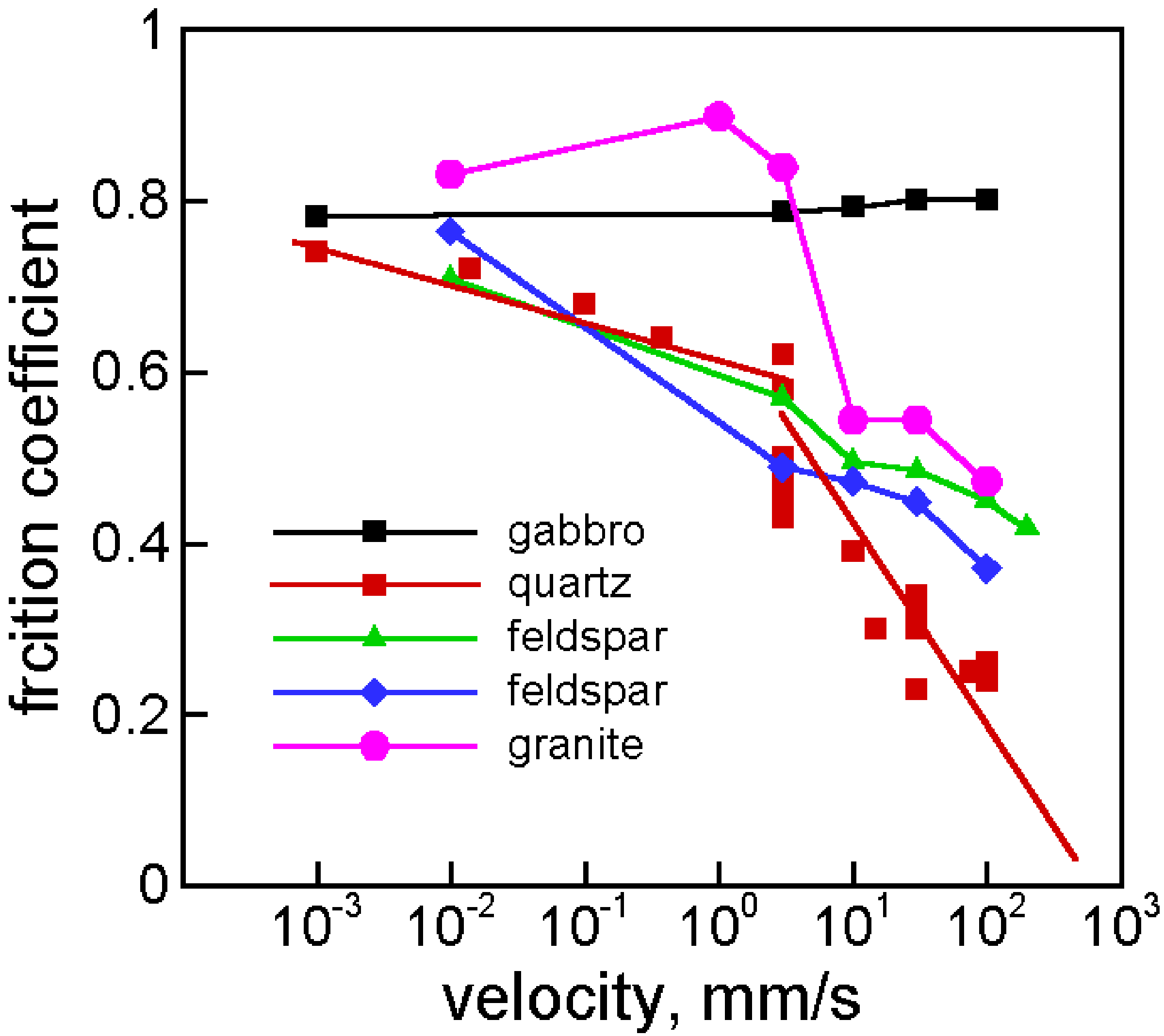
(Hibi & Enomoto, 1999, Wear)



SiC in H2O

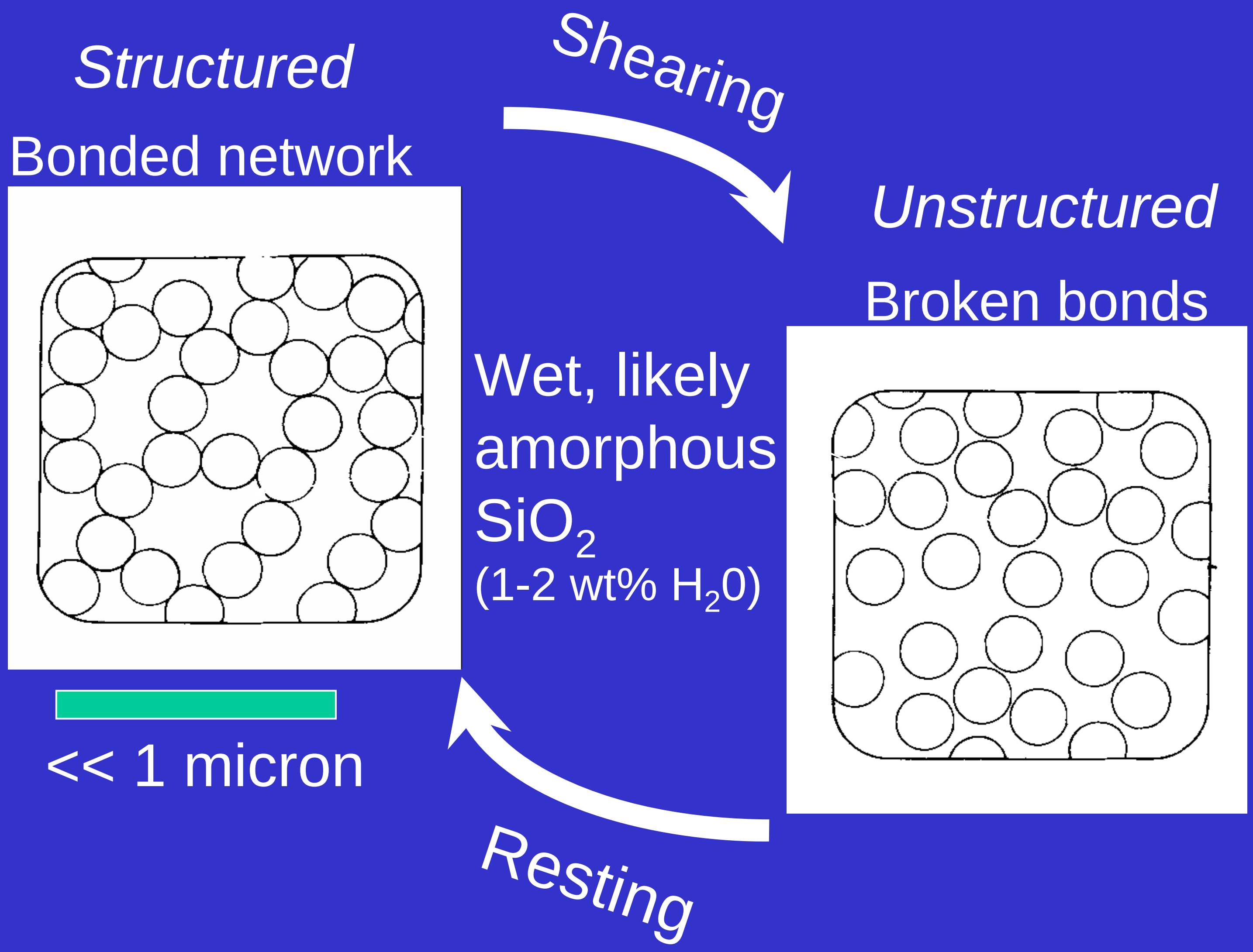
(Kitaoka et al., 1994, J. Am.Ceram. Soc.)

Many crustal rocks weaken at high slip rates



[Roig Silva et al., AGU 2004]

Thixotropy of silica gel

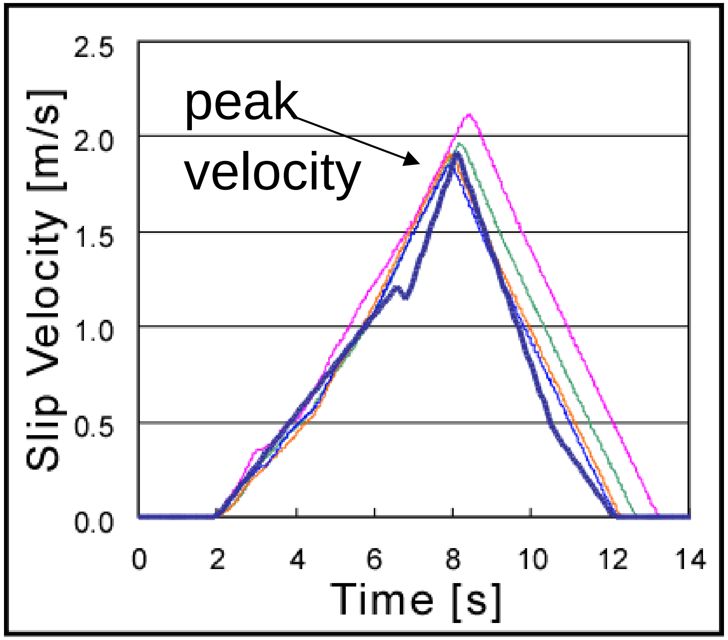


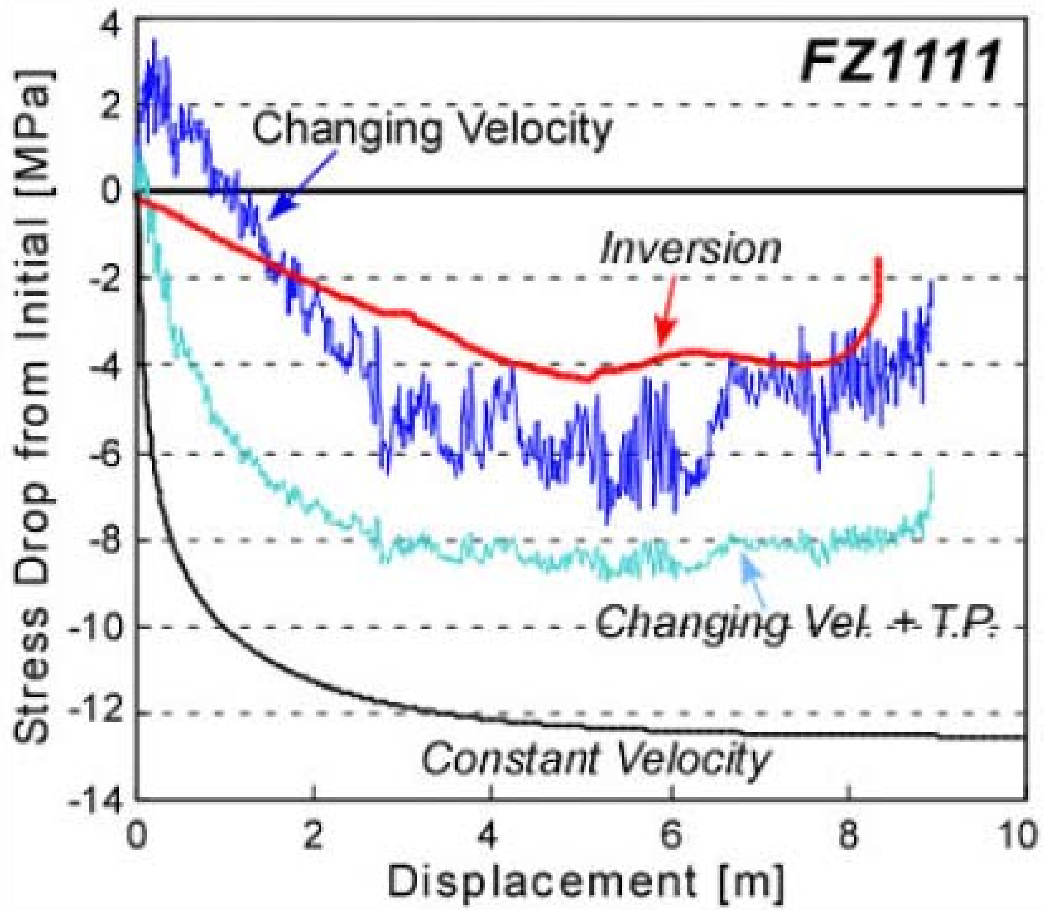
Stress drops determined by reproducing inversion-derived particle vel. (Chi-Chi 1999 EQ, Ma et al.) are smaller than those obtained at constant slip rate (1 m/s).

Inversion-Derived Particle Vel.

Normal Stress: 0.6 MPa

Clayey Fault Gouge





Sone et al., AGU 2005

Slip rate and shear stress determination in solid specimens: equivalent slip velocity

$$v_e = \frac{4\pi \ R\, r_2}{3}$$

$$\tau = \frac{3\ M}{2\pi\ r_2^3}$$

R = rotary speed

r_2 = outer sample radius

M = torque

Cylindrical and hollow shaped specimens yield very similar results.

As aluminum melts at 650 ^{o}C, the external aluminum outer ring sustains the sample during initial sliding only.